Enabling Innovation on the UK Railway: A Critical Approach

By

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Abstract

Enabling innovation in the UK railway.

The major impact of a range of factors, such as political uncertainties, economic difficulties, and the covid pandemic, have hit the UK railway hard, requiring the sector to address its costs and improve its performance. This has made innovation a necessity rather than choice for the sector. However, introducing innovation seems to be accompanied with greater complexity and complication in a complex system such as the railway.

This thesis seeks to analyse and explain the fundamental operation of innovation in the context of the UK railway sector, to identify and address the issues and barriers existing in the rail industry that challenge the introduction of innovations onto the railway, and to develop a conceptual framework to explain how innovation works and how more innovation can be enabled more successfully. The ambition for the framework is to act as a foundational piece that can go on to facilitate innovation in the global rail industry.

A systems approach has been adopted for the research methodology. The research reviews existing literature in the field of innovation generally and its application to the railway specifically. Mixed research methods are applied to collect, observe, and analyse the primary and secondary data to provide a broad evidence base to support the development of a model of the current UK railway innovation landscape, from which the conceptual framework is developed. Significant new quantitative and qualitative data contributes new knowledge in the field of rail innovation, as does the development of the model and the conceptual framework setting out railway innovation.

This research uses a critical approach to establish a conceptual framework that explains the process of rail innovation, and that significantly enhances the understanding of the key roles of actors and institutions that can accelerate and/or de-risk implementation processes for innovation on the railway. The framework is tested and validated to demonstrate its relevance to the proposed application of railway innovation.

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Declaration and Statements

"I, Alexander Burrows, do solemnly and sincerely declare that the research undertaken and presented is original and I make this declaration conscientiously believing the same to be true."

Alexander BURROWS

Birmingham, 18 March 2025

Confidentiality Statement

All data that was collected in the conduct of this research will remain strictly confidential and has been collected, stored, and used, ensuring anonymity and protecting participant privacy. Participants gave informed consent, and all participant data will be kept strictly confidential and in full compliance with GDPR and all other relevant obligations.

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Chapter 1: Introduction

Chapter Structure

1.1 Introduction

The railway is a critical mode of transport capable of moving huge numbers of people and large volumes of freight through cities or across continents in a fast and efficient manner. In 2025, the UK railway celebrates 200 years of operation (Railway 200 2025) since the Stockton and Darlington railway opened becoming the first public railway using steam locomotives in regular operation (ICE 2025).

The railway has grown and developed significantly in those 200 years, not least the technological advances that have occurred that have fundamentally shifted both operations and expectations. The technology used by the railway (beyond the steel wheels on steel tracks) has advanced - from steam to diesel and electric traction power, the signalling systems, information systems, asset management and monitoring, and across all fields of operation, we can identify clear advances that have utilised state of the art technologies to improve services.

These advances have come through innovation – identifying new products and processes and then applying them to create an improvement to the existing state of the art. The railway has used technology to compete with other modes of transport – from the horse to the car, to the plane – as an effective means of moving people and goods.

Now more than ever, the UK railway needs to use innovation to deliver an efficient and effective mode of clean, public transport. As technological development continues at a rapid pace, threats to the railway continue to emerge from technological innovations including the potential for autonomous road vehicles, to the commercial innovations enabling business models that see flying as a cheap mode of medium and long-distance travel.

The railway needs effective innovation that delivers the right product at the right time to an industry that can welcome and adopt these opportunities to further improve and enhance its operations and offer to the market. How do we achieve that? How do we get effective innovation taking place that can deliver railway applications that achieve the outcomes we, as an industry, want to see? How can we fully realise the benefits of innovation activities and increase our chances of success?

If the railway is to continue to thrive as an efficient means of moving large quantities of people and goods into and between cities, and across countries, then it needs to compete effectively with all other modes of transport. This requires it to meet two major challenges head on:

(1) The first is to provide a good service to customers (be they passengers or freight) that is clean, safe and reliable, with up-to-date information and the facilities that are expected in the 21st century.
(2) The second is to provide that service as cost-effectively as possible, making it affordable both for customers, and to achieve as much as possible to justify the significant capital and operating expenditure that railways require.

Both challenges require solutions that are constantly emerging to provide ongoing improvements – improvements that have been sought many times by politicians, such as in the Williams Shapps Plan (Department for Transport 2021) and in the current plans for railway reform (Great British Railways 2025). That is the role for, and the requirement of, innovation for the UK railway.

Research has been defined as “an orderly investigative process for the purpose of creating new knowledge” (Swanson 2005). This research seeks to analyse the issues and barriers to introducing innovation onto the UK railway; the aim is to use this analysis to then develop a framework for enabling and facilitating the introduction of more innovation, more effectively and successfully, into operation on the UK railway. This research will use an ‘orderly investigative process’ to develop such a framework that will provide new knowledge and insights to enable more successful innovation.

In this chapter, the background to the research is introduced, followed by the objectives for the research and the questions it seeks to answer, the approach and methodology proposed, and the scope of this research project.

1.2 Research Background

1.2.1 The UK railway context

The UK railway, at the time of writing, is facing the significant combined challenge of being required to improve its operational performance to both increase efficiency and reduce costs. Following the 2024 General Election, the incoming Government was required to undertake a full review of spending across all areas of Whitehall (HM Treasury 2024). Within transport, rail faces strong competition for major infrastructure investment including from the High Speed 2 major project as well as all other modes of transport. It also needs to convince the Treasury that it is a sensible strategic investment providing good value for taxpayer money.

The numbers are in question are large: in Control Period 7, the five-year operating period from 2024 – 2029, Network Rail will spend just over £45bn on railway operations, maintenance, and renewals (Network Rail 2024); while phase 1 alone of the new High Speed 2 railway line is forecast to cost around £57bn (Public Accounts Committee 2024).

Figure 1.1 shows a high-level summary of the Department for Transport's expenditure in 2023-24 with rail (in green) consuming £30,125m of a total £44,624m (67.5% of Government spending of transport).

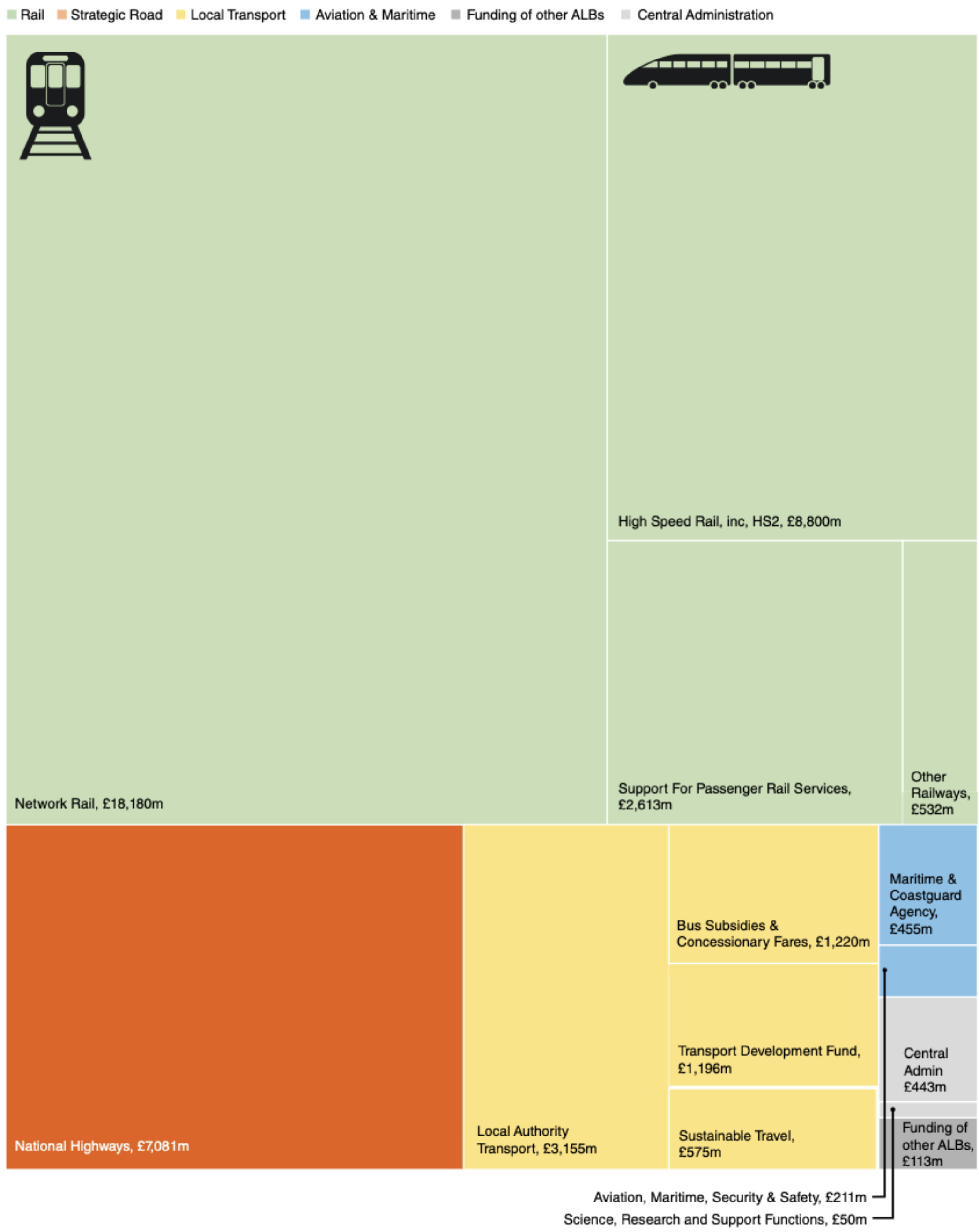

Figure 1.1: Department for Transport Annual Expenditure 2023-24 (Department for Transport Annual Report and Accounts (2024))

To address the costs of running the UK railway, particularly considering the massive negative impact of the covid pandemic on railway operating costs in 2020, the UK Government published the Williams Shapps Plan for the UK railway in 2021 (Department for Transport 2021) setting out a clear challenge to the rail industry to urgently modernise. The Plan set out a new approach to reform the UK railway. A new entity, Great British Railways, is to be established that will assume many of the responsibilities from Network Rail for managing the UK's railway infrastructure, as well as taking over the management of passenger railway operations, thereby integrating the complete oversight of all railway operations and infrastructure within one body. At the time of writing, the Great British Railways Transition Team continues to develop its plans to implement this major reform programme (Great British Railways 2025).

The UK railway is frequently announced, reviewed, and reported as being in need of innovation to improve its operations and processes (for example: Williams Rail Review, Department for Transport 2019; Shaw Report, Department for Transport 2016; Department for Transport 2012; McNulty Report, Department for Transport 2011). The common and recurring goal is the need to reform the railways to increase passenger and freight use and therefore revenues, to then reduce the burden on public expenditure.

The desire and indeed explicit demand for innovation to be used to support the delivery of these outcomes is clear. But undertaking innovation and then introducing it to the UK railway is a complex process fraught with significant barriers – and these barriers appear to be effective in meaning that the desired outcomes are not achieved, thereby requiring another announcement, review, and report to highlight this!

This research aims to investigate the systemic problems that have created a continuous cycle of demand for innovation in the UK railway but with apparently little success in delivering it.

The UK railway receives public support and investment to enable innovation – for example the Innovate UK funding streams, a summary of which is illustrated in Figure 1.2.

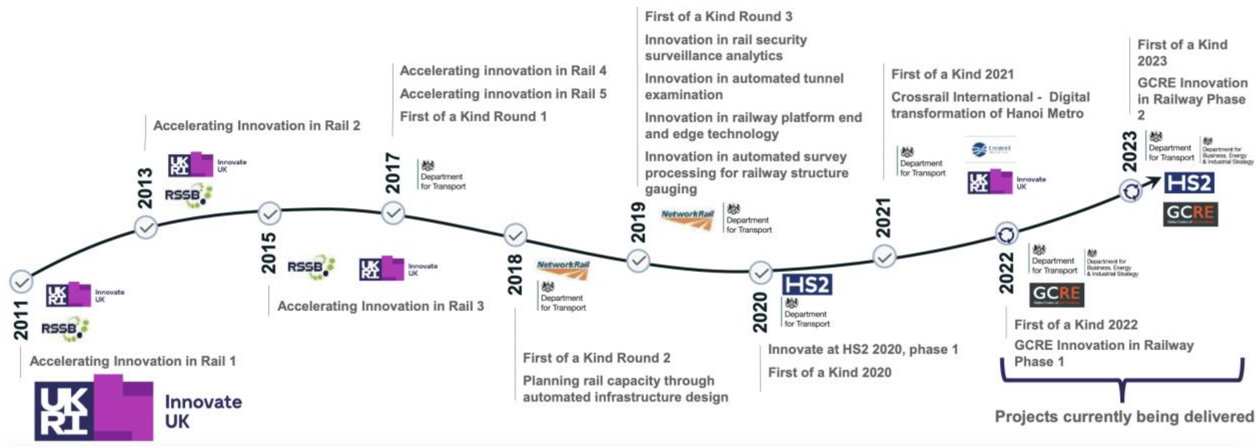

Figure 1.2: Timeline and summary of the main competitions Innovate UK has supported and partnered in with other funders to enable innovation in UK rail (GCRE presentation to the Permanent Way Institute, 14 March 2024 – Davies 2024*)*

To contextualise, the seven rounds of the annual First Of A Kind funding competition for the rail sector comprised a combined UK Government investment of £44,140,505 (table 1.1).

2017 FOAK1 (10 projects)	£3,369,962
2018 FOAK2 (10 projects)	£2,763,879
2019 FOAK3 (25 projects)	£8,062,487
2020 First of a Kind (25 projects)	£8,806,776
2021 First of a Kind (33 projects)	£9,496,706
2022 First of a Kind Phase 1 (24 projects)	£5,016,382
2022 First of a Kind Phase 2 (2 projects)	£1,479,063
2023 First of a Kind (18 Projects)	£5,145,250

Table 1.1 Innovate UK Rail First Of A Kind competition funding (2017 – present) (Innovate UK 2024)

By comparison, the automotive sector in the UK can count on government investment to support innovation through several channels including the Advanced Propulsion Centre (APC 2024), an agency established to “collaborate with UK government, the automotive industry and academia to accelerate the industrialisation of technologies, supporting the transition to deliver net-zero emission vehicles” (APC 2024). The APC is currently managing £850 million funding (APC 2024) to decarbonise the industry and its supply chains – a huge number, for context, that is over 10% of total annual national highways spend (see Figure 1.1).

This research will compare the role and operation of the innovation systems in adjacent industries, including automotive, to understand the similarities and differences with the railway sector.

There are plenty of examples of successful innovations introduced into the UK railway sector over the last 200 years (starting with the first steam-powered locomotives through to the Intercity125 High Speed Train in the 1970s, the establishment of the standard railway gauge, the form of block signalling, the opening of the London Underground and the first electric underground railway), and, the UK railway industry remains recognised as a home of significant technical and engineering railway expertise (for example, Adams 2016). But the translation of research and innovation onto the operational railway remains comparatively difficult, with several factors to blame including high barriers to entry, high risk, slow pace, system complexity, and political uncertainty (for example, Railway Industry Association 2022, Great British Railways 2024, Rail Supply Group 2016).

This research seeks to identify why this is the case and how this can be addressed.

1.2.2 Why does the railway need innovation?

Innovation can be defined as the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations (Eurostat, 2005).

The OECD have also provided a more detailed definition:

"Innovation means the successful development and application of new knowledge. It therefore involves more than just invention. Fixed capital investments are often necessary for producing and using new products and processes, as are employee training and organisational restructuring. It is convenient to view innovation as a process that involves many different stages, from research and development (R&D) to the development of prototypes, patent application, and finally, commercial applications." (OECD 2008).

The purpose of innovation is to establish a beneficial change to the existing way of doing things. They can be evolutionary, creating incremental improvements, or they can be disruptive, being radical and creating a major shift in the normal practices, however the pace of innovation does not affect the definition of (or the need for) innovation itself.

From the perspective of the railway, there are three major drivers that create a motivation for innovation on the railway (Burrows et al 2022):

(i) Opportunities to exploit technological advances;
(ii) Growing competition from other forms of transport; and,
(iii) The impact of unforeseen exogenous shocks (such as a global pandemic).

Each of these can establish a clear demand for innovation:

Opportunities to exploit technological advances

The 21st century has set an accelerated pace of technological advance that has seen the rapid adoption of smartphones supported by several core technologies (for example cloud computing, big data analytics, artificial intelligence) that offer vast opportunities. These opportunities can manifest in the railway context in a huge number of ways such as vastly improved passenger information and real-time communications, or asset condition monitoring and management, or dynamic traffic operations control and management systems. The railway could effectively use these advances to deliver improved services to customers, to reduce its operating costs, and to increase the efficiency, safety and reliability of its trains and network.

Growing competition from other forms of transport

The railway is under pressure from other transport modes on two fronts. The first front is other modes of transport developing and deploying these new technologies more quickly and effectively to provide sterner competition to the railway. For example, the promise of autonomous road vehicles using battery technology to provide clean and efficient transport solutions is routinely used, particularly in urban areas to rival the railway (Wiseman 2019). But it also includes using technology to deliver a better offering to passengers such as reliable Wi-Fi connectivity, and a reliable and frequent service. The second front is from operating costs and business models. The railway is expensive to run with fixed infrastructure and major capital and operating spend required. As such, it requires public policy support to enable it to compete through policy design and interventions that establish how public spending is allocated to invest in railway services, focused on demonstrating the public good of allocating such investment in supporting a wide range of positive social, economic, and environmental policy outcomes (Alhassan 2024).

The impact of unforeseen exogenous shocks

The impact of a global pandemic on railway services was, unsurprisingly, negative. The railway lost its patronage overnight due to lockdowns and has taken time to come back towards pre-pandemic levels (table 1.2) due to changes in working practices, combined with reticence to continue with public subsidies to maintain service levels.

Time Period	UK rail passenger journeys (millions)
April 2013 – March 2014	1,583.4
April 2014 – March 2015	1,650.4
April 2015 – March 2016	1,713.5
April 2016 – March 2017	1,727.5
April 2017 – March 2018	1,704.0
April 2018 – March 2019	1,753.0
April 2019 – March 2020	1,738.7
April 2020 – March 2021	387.9
April 2021 – March 2022	990.1
April 2022 – March 2023	1,384.8
April 2023 – March 2024	1,612.0

Table 1.2: Office of Rail and Road statistics (excerpt from table 1220) (Office of Rail and Road 2024)

In the period following the covid pandemic, the UK railway has required significant public funding to subsidise its operation (see below) and, in tandem with government policy looking to make savings, this has caused the railway to have to balance a reduction in income with the need to effectively maintain service levels.

Table 1.3 illustrates the major shift in the quantum of government funding required to keep the railways operating during and after the covid pandemic.

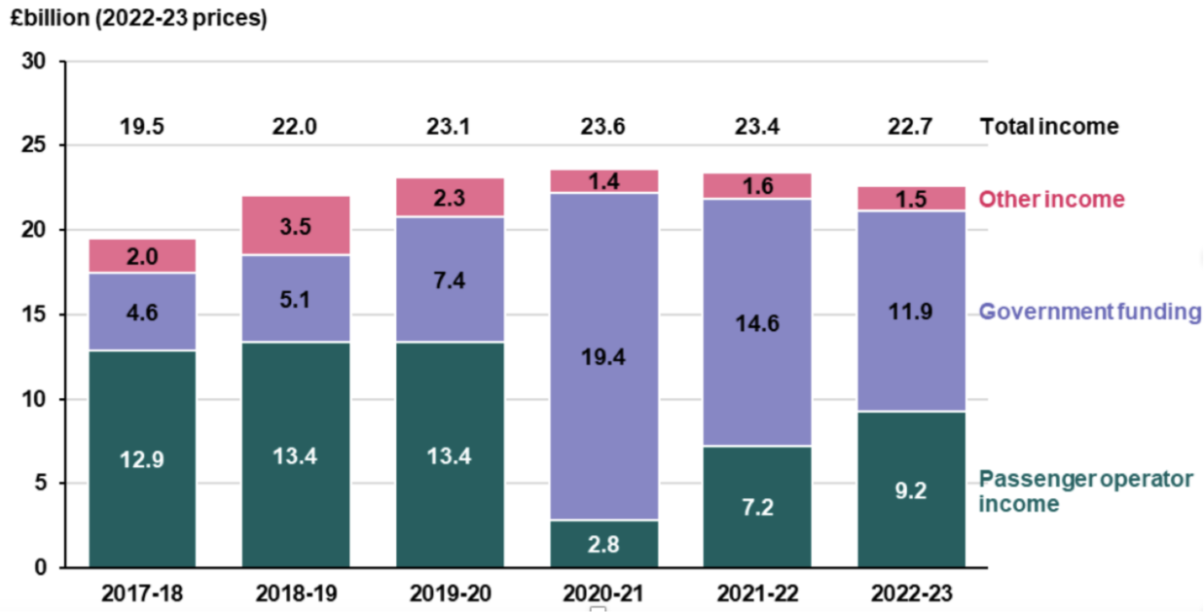

Figure 1.3: Income for the operational rail industry, UK, annual data, 04/2017 – 03/2023 (Table 7210), Rail Industry Finance (UK), (Office of Rail and Road 2023)

Taken together, all three of these drivers have caused a range of problems for the UK railway and thereby providing significant motivation to use innovation to try and find creative solutions to these problems.

1.2.3 The railway as a complex system with a complex network of actors

The UK railway is a complex system (Bešinović 2020) combining critical transport infrastructure that provides vital connectivity for passengers and freight, with a large and varied network of actors and stakeholders, and often described in terms such as, *"too complicated, too confusing for passengers, too expensive to run and improve, too difficult to lead, and too hard to reform"* (Department for Transport 2021).

The current structure of the UK rail industry is in a state of flux at the start of 2025; figure 1.4 below illustrates its complexity in 2021, currently the interim state post-pandemic and prior to the introduction of Great British Railways. The seismic impact of the covid pandemic and several changes of Government have led to significant changes to the reform programme that was initiated by the Williams Shapps Plan and that will eventually lead to the establishment of Great British Railways.

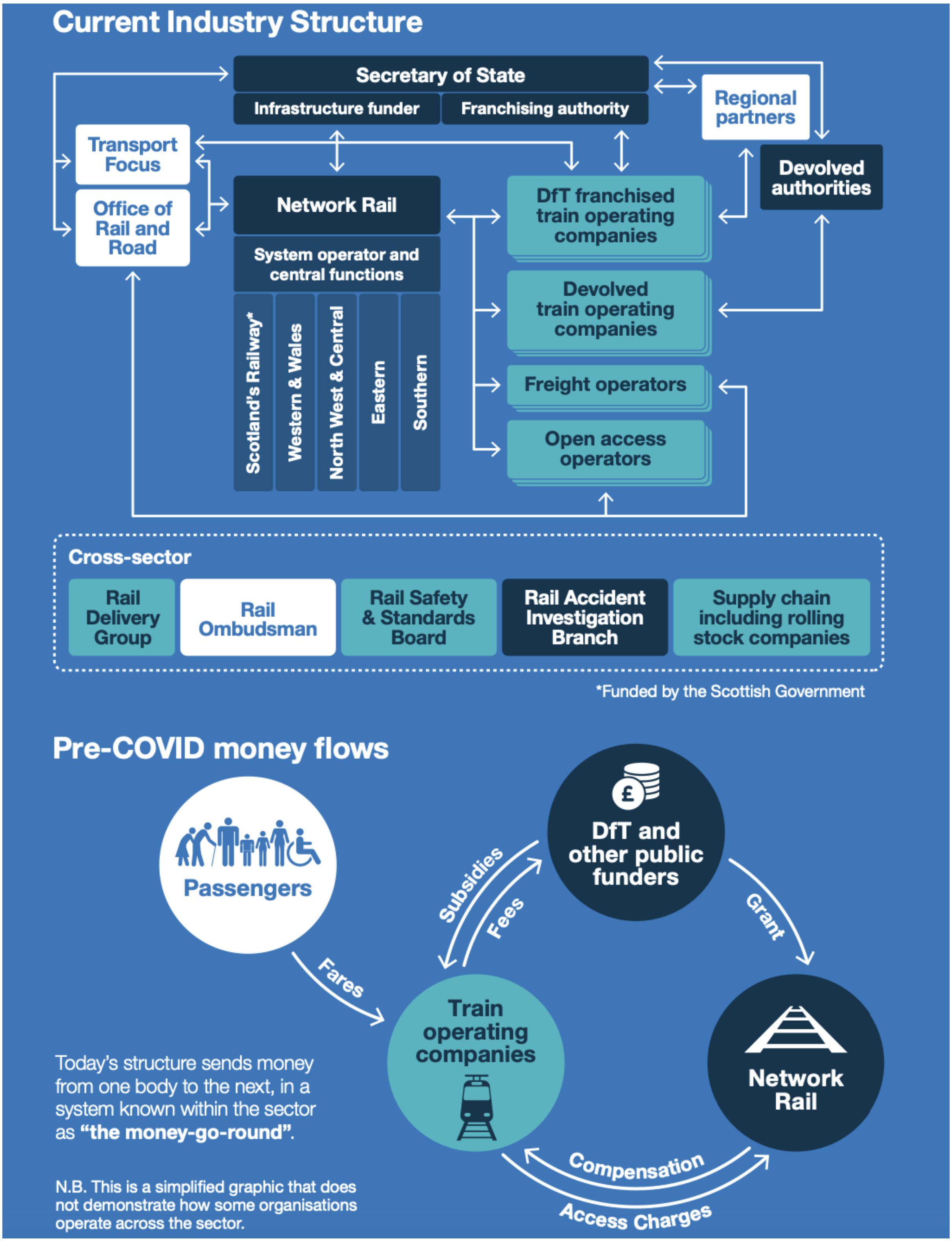

Figure 1.4: The UK railway industry in 2021, (Department for Transport 2021)

Figure 1.5 sets out the future structure of the UK railway envisaged by the Williams Shapps plan. Four years later, the Great British Railways Transition Team is still developing these complex plans for fundamental reform of the railway amid a backdrop of relative political stability following the 2024 General Election.

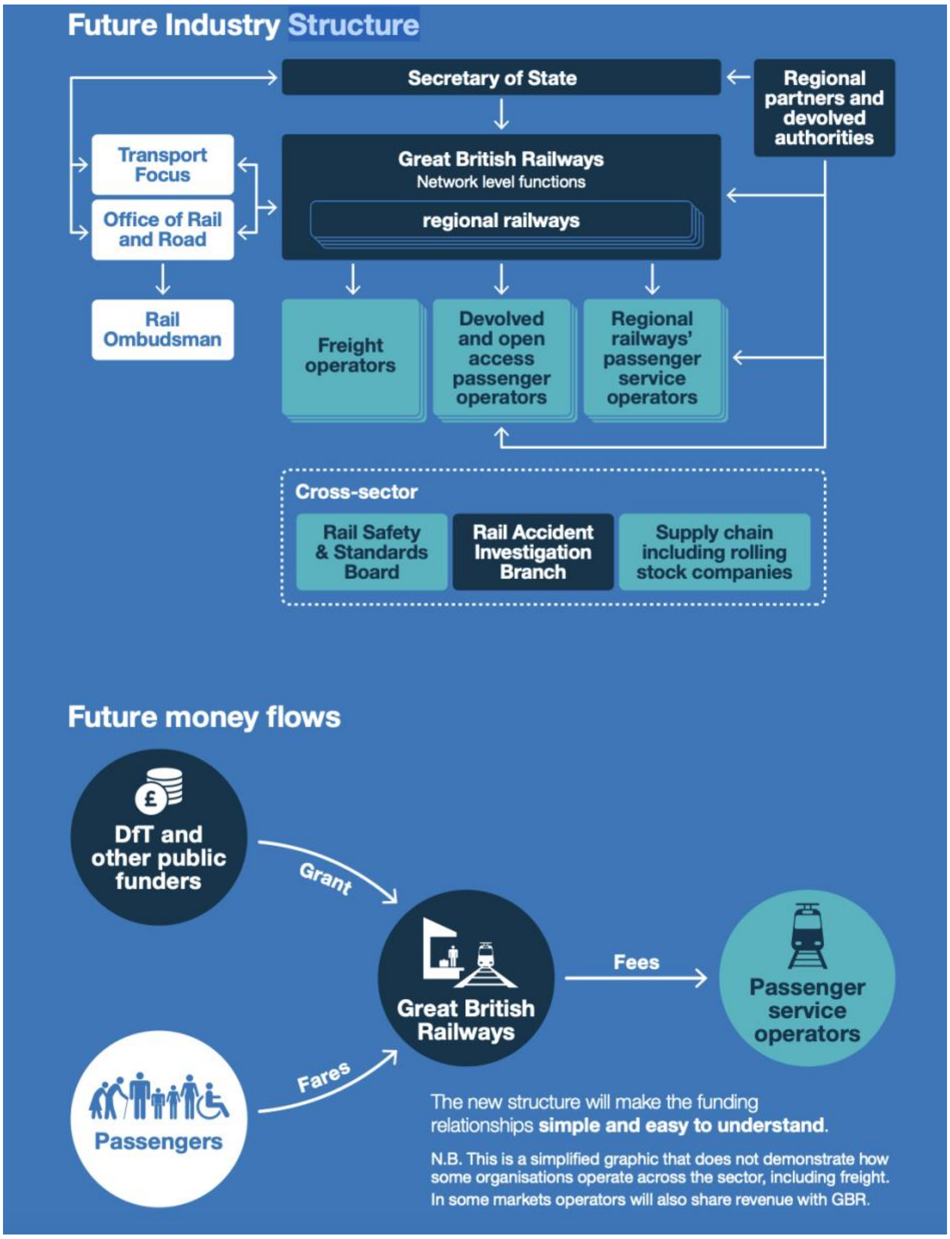

Figure 1.5: The envisaged future UK railway industry, (Department for Transport 2021)

Great British Railways is developing a long-term plan based on five strategic objectives (Great British Railways 2025):

(i) Meeting customers' needs – with the demand for the railway to improve its offer by delivering better value for money as well as improving its performance and reliability.

(ii) Financial sustainability – clearly stating the need for railway operations to improve their efficiency and value for money; delivering projects on time and on budget; and reducing costs to Government.

(iii) Long-term economic growth – specifically referencing improved performance and reduced cost for users, and *"catalysing long-term economic growth by… directly investing in skills, innovation and digital infrastructure…".* (Great British Railways 2025)

(iv) Levelling up and connectivity – specifically referencing the role of rail in providing connectivity for passengers and freight; and its role in social equity.

(v) Environmental sustainability – specifically referencing the need for making rail attractive to encourage modal shift from alternative modes of transport; achieving; Net Zero operations; and the need for adaptation to manage the impacts of climate change.

These expectations were summarised by the then-Secretary of State for Transport at the end of 2024,

"As part of this Great British Railways (GBR), as the single directing-mind, will plan services on a whole-system basis, to better deliver for passengers and freight customers, unlock growth, and provide the services a modern, efficient railway should.

This will lay the groundwork for the introduction of the Railways Bill later this session, which will establish GBR and end the fragmentation that has hampered our railways for over 30 years of privatisation." (Haigh 2024)

The root cause of the problem from the political perspective is clear, the fragmented structure of the railway industry caused by the privatisation of the railway in the 1990s.

Privatisation had been introduced as a means of reducing the operating cost of the railway on the taxpayer - after thirty years, this has not been achieved (Montero and Finger 2020). The role of Great British Railways (GBR) is to provide a structural remedy to that, as envisaged by the Williams Shapps Plan that established GBR in 2021.

The complexity of the railway as a whole system is two-fold:

- The complex structure of the UK railway - as discussed above - creates difficulty in aligning risk and reward, of identifying accountability and responsibility, and of delivering change and improvements.
- The complex operations of the railway are increasingly stretched by rising transport demand, brought about by increases in population and urbanisation, with more demand for sustainable transport services, and concerns around affordability and reliability (Bešinović 2020).

In this context, the demand for innovation to help address these issues on the UK railway is clear. But these two-fold layers of railway system complexity negatively impact on the opportunity for innovation.

In the structural context, the UK railway struggles with the need to incentivise and enable innovation in response to the finding that the UK railway struggles to innovate due to diverging responsibilities and priorities for R&D and innovation, as well as needing to build stronger links between the innovators, i.e. the suppliers of innovation, and the end users, i.e. the demand for innovation (Department for Transport 2021).

In the context of the complex system of railway operations, this is a system with strict rules on product introduction and approvals, with high barriers to entry, and where the landscape is relatively challenging and unattractive for new entrants to the railway sector.

Multiple reviews of the UK railway have identified the need to incentivise innovation, that there are fragmented priorities and responsibilities for R&D and innovation across the industry, with a huge gap between the suppliers of innovation and the users of innovation (for example, Rail Supply Group 2016, Department for Business Energy and Industrial Strategy 2018, Department for Transport 2021). The continuing reoccurrence of the same principle as a key part of rail reform clearly indicates that it has not been achieved.

But the opportunity for the railway to positively be able to use innovation to deliver its objectives, if these challenges can be addressed, is clear – with the increasing challenge of decarbonisation requirements, and the tangible opportunities that digitalisation offers, providing clear targets for the UK railway to focus on (Montero & Finger 2020).

Figure 1.6 illustrates the range of actors and stakeholders whose role must be understood by any organisation seeking to enter the UK railway market with innovative products and services.

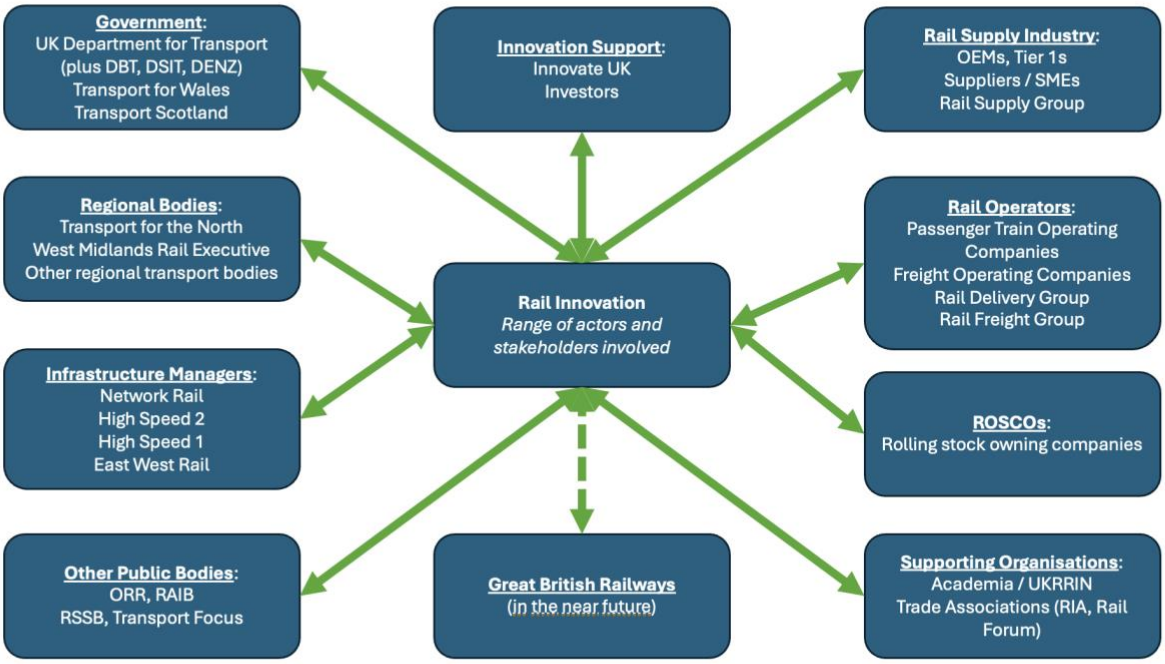

Figure 1.6: Illustration of the range of actors and stakeholders involved in UK rail innovation in 2024

The scale of the UK railway sector and the breadth of organisations with a role to play, or any kind of influence, on railway innovation is evident. The difficulty for a new entrant to the railway sector in trying to comprehend and navigate such a complex system, compared to an organisation with prior knowledge, must be recognised and understood. In recognising that the railway needs innovation, we also need to understand how to enable and support that innovation in the context of the railway as a complex system. This research seeks to investigate that issue.

1.2.4 What can we learn from history?

The invention and development of the railway as we know it took place in the UK in the first half of the nineteenth century. Over the last two centuries the technology has evolved significantly with technological advances delivering faster, cleaner, safer transport for people and goods.

As the railways developed, demand for research and innovation came from the railway companies who established their own in-house capability as the networks quickly grew in competition with each other as well as with other modes of transport (Gilchrist 2009).

Following the nationalisation of the UK railways in 1948, railway research was gradually centralised into the British Railways Research Department (initially the Railways Executive Research Department) and its role and value was recognised as significant in enabling the delivery of the 1955 Modernisation Plan (Gilchrist 2009). The introduction of diesel and electric locomotives as well as significant advances in infrastructure technologies covering track, structures, and electrification created demand for research and innovation to deliver a modernised railway (Gilchrist 2009). The royal opening of the new Engineering Research department facilities in Derby in 1964 demonstrated the prominence and importance of research and innovation in the operation and development of the UK railways at that time.

Up to that point, the funding for research and innovation had come from the railway itself with these activities being driven and delivered to meet the requirements of internal customers. Between 1965 and 1969, the Research Department actively lobbied the Ministry of Transport for direct funding to augment the railway's own investment in research. The proposal focused on meeting strategic research needs to address national ambitions for increasing the speed of surface transport. The success of this led to the funded research programme that delivered the Advanced Passenger Train and the establishment of the railway test track and facilities at Old Dalby (now one of two Rail Innovation and Development Centres owned and operated by the UK rail infrastructure manager, Network Rail) along with a significant volume of rail research over the next sixteen years (Gilchrist 2009).

With the privatisation of the railways in the 1990s, the Research Department was separated from the operating railway and sold to private industry. This severed the link between applied railway research and the end user for the first time in the UK.

Since then, the demand for innovation has continued to exist but in a separated manner from the supply of innovative solutions, creating a gap that had not previously existed in the UK railway innovation landscape.

1.2.5 Regulation and the experience in adjacent industries

Transport is a heavily regulated sector for a number of reasons. Transport is an essential part of all our lives and plays a critical role in sustaining and enhancing quality of life through access to employment, education, and leisure (Bešinović 2020). It plays a key role in enabling and supporting many positive social, economic, and environmental outcomes. It is transport's importance in the health and wealth of nations that make regulation both desirable and inevitable (Padam 1998).

To provide relevant context, the adjacent transport sectors of automotive, aerospace, and maritime, provide instructive parallels and a brief comparative analysis can highlight issues that are common with the railway sector, as well as differences that create the unique context for the railway. Transport regulation is required to uphold safety standards, manage environmental impact, support social and economic objectives, enable public access and connectivity, and manage networks for the good of all – including the operation and forward planning of investment in transport infrastructure. But how this regulation is undertaken varies across transport modes.

While the UK railway is heavily regulated with government control over all aspects of both operations and commercial activities (Nash & Smith (Montero & Finger 2020), the automotive sector is less directly controlled. The automotive sector is regulated in several key areas including on safety standards, emissions and environmental standards, and product standards and approvals – all of which are analogous to the railway's experience.

From a commercial perspective, the UK railway is firmly controlled by the Government with many types of fares and services directly specified and contracted to private operators for delivery, leaving little freedom for private companies to operate under their own auspices, and stifling any demand for innovation in the process (Stephenson Harwood 2024).

Conversely, the UK automotive sector is free to operate in a private, commercially competitive market. Revenues are driven purely by customer demand alone rather than government-specified contracts for services.

The automotive industry has visibly sought to use innovation to apply technological advancements into both their manufacturing processes and their product offering. This is motivated by a highly competitive market with freedom to operate, and freedom to invest in innovation to create a direct advantage quickly. In the area of manufacturing, robotics, lean manufacturing, and 3D printing have revolutionised production lines (Bhattacharyya 2015). In the product area, the sector is currently transitioning from combustion engines and analogue technologies to electric and connected vehicles. The automotive industry has focused heavily on both electric vehicle technologies, to phase out exhaust emissions, and to deploy connected and autonomous driving systems, to improve customer experience and vehicle reliability, both in response to market demand and regulatory pressures (OECD 2023, Winnett et al 2017).

While both the railway and automotive sectors must meet regulatory standards, the automotive sector has much more commercial freedom within which to operate. This enables greater freedom to rapidly invest in innovation to gain competitive advantage in a dynamic market.

Investment in rail innovation is heavily influenced by the UK government and its policy objectives and signals to the market; by contrast, automotive innovation is purely driven by commercial imperatives alone (Winnett et al 2017).

Like the railway and automotive sectors, the aerospace sector is regulated as an important and safety-critical mode of transport. Unlike the others, the sector has multiple layers of regulation with both national bodies (e.g. the UK Civil Aviation Authority) and international bodies (e.g. the International Civil Aviation Organisation and the European Union Aviation Safety Agency) having regulatory functions over aerospace businesses.

As with automotive, the commercial environment for aerospace is a private, dynamic market where both service operators and the supply industry are businesses looking to gain advantage in a highly competitive global market (Caliari et al 2023). Innovation is therefore driven by commercial imperatives within the aerospace sector, rather than by government objectives as in rail.

The aerospace sector is a research-intensive industry and an exemplar of using innovation from technological developments across many areas such as lightweight materials, fuel-efficient engines, and aerodynamics (Pereira et al 2022; Caliari et al 2023). More recently, the sector has utilised emerging digital technologies such as digital twins and advanced simulations to make improvements in maintenance and design (Pereira et al 2022). In addition, current efforts to decarbonise have seen a major focus on reducing emissions through the application of electric and hydrogen technology – an example in the UK is Zero Avia (https://zeroavia.com) who are developing electric and hydrogen-electric powertrains for aerospace applications.

Like the other sectors (particularly rail and aerospace), the maritime industry is tightly regulated, although within an international (rather than national) regulatory framework. The International Maritime Organisation centrally convenes the global regulation of shipping under the authority of the United Nations and includes comparable safety and environmental standards (MARPOL) that create a consistent global regulatory framework for all shipping (Baumann 2023).

Maritime is a competitive commercial market with little government control, instead market forces create a dynamic market that private companies must respond to – not just within the maritime industry but with road freight transport as a significant competitor (Alvarez-Sanjaime et al 2013). This creates the same incentives for innovation faced by aerospace to ensure that operating companies maintain competitive advantage through the most efficient and effective operations, thereby using new technologies to best effect. The global focus on requiring decarbonisation of industries, such as maritime, has led to a renewed focus on the use of innovation to improve industry performance (Wang, Cheng, Zhen 2023; Perunovic & Vidic-Perunovic 2011).

As in all other transport sectors, maritime is having to address its environmental performance which has incentivised investment in low-emission fuels, including LNG, biofuels, and hydrogen, to meet emissions targets set by the IMO (IMO 2024; Wang, Cheng, Zhen 2023). Similarly, the development of digital technologies has provided opportunities to benefit shipping operations, for example through application supporting autonomous ships and integrating artificial intelligence to optimise route planning and cargo handling.

Assessing the relevant factors that shape the UK railway in comparison with these three adjacent transport sectors, there is a clear distinction that indicates the different context and influences impacting on the railway specifically, summarised in table 1.3.

Rail	Automotive	Aerospace	Maritime
Primary regulatory drivers (safety and environmental)			
Domestic	Domestic	Domestic & International	International
Role of UK Govt public policy			
Major – policy objectives drive funding decisions	Minor – influence through regulation	Minor – influence through regulation	Minor – IMO as a supranational regulatory organisation manages this.
Market context			
Domestic - low volume sales, UK Govt directs procurements	Domestic – lower value but high volume sales direct to end-users	Domestic (defence) & Global (commercial) - lower volume, higher value	Global - lower volume, higher value
Cost drivers			
Government looking for lowest cost; balance against wider public spending requirements	Market-driven - can assess whole life cost and benefits	Market-driven - can assess whole life cost and benefits (nb defence industry public spending is significantly greater than for rail)	Market-driven - can assess whole life cost and benefits
Supply industry (manufacturers and supply chains) drivers / innovation drivers			

Mostly UK Government-led procurements with detailed specifications / requirements (TOCs, HS2, Network Rail)	Private companies looking to gain competitive advantage	Private companies looking to gain competitive advantage	Private companies looking to gain competitive advantage

Table 1.3: summary of headline factors influencing railway and three adjacent transport sectors

1.3 Research Scope and Objectives

The aim and purpose of this research is to answer the question, 'how can more innovation be successfully introduced onto the UK railway'?

The research therefore seeks to understand the current landscape for innovation in the UK railway, and to identify the factors that either enable or block innovations from succeeding.

The scope of this research project is innovation in the UK railway - the UK railway system in the widest sense, i.e. the entire sector (incorporating both railway operations and the rail supply industry), is the subject matter for this research. The research will build a model of the UK railway system and the role that innovation plays in that.

From that model, a conceptual framework will then be designed that places the role and purpose of innovation, and correspondingly, how innovation can support the objectives of the UK railway. To build an effective conceptual framework, the research will also consider international railway systems and adjacent industries to provide a richer comparative understanding and context.

The objectives of this research are:

- To undertake a review of the relevant literature relating to models of innovation to provide a deeper understanding of how innovation is undertaken and deployed to create value through improvements to products, processes, and solutions.

- To undertake an analysis of innovation in the railway sector, focusing firstly on the UK system and then an overview of other systems, and other adjacent industries, to provide a comparative analysis of innovation theories in application.
- To undertake a detailed analysis of the UK railway sector, using a combination of research methods, to develop a model of the UK railway innovation system.
- To identify the enablers, barriers, and sector complexities, that impact on the success of innovations in entering the UK railway market.
- To develop a conceptual framework that uses a model explaining the UK railway innovation landscape, and that highlights the enablers and mitigate the barriers and complexities to innovation, in order to design a conceptual framework of how the UK railway innovation landscape ought to be to enable the more effective introduction of innovation onto the UK railway.

1.4 Research Questions

The hypothesis for this research is that the UK railway needs to be more effective in supporting relevant innovation to happen, and to better enable it to be introduced successfully into deployment, in order to meet the expectations of politicians, stakeholders, and the general public, to deliver a railway that provides better services for passengers and freight, and that those improved services are delivered at a lower cost.

To test this hypothesis, five research questions have been developed to frame the research.

The first three questions are all focused on developing the empirical evidence base to inform a descriptive analysis of what the UK railway innovation landscape looks like.

- **RQ1: How is innovation currently supported and enabled, or not, to be introduced onto the UK railway?**
- **RQ2: What are the critical factors that act as either enablers or blockers to innovation successfully being introduced onto the UK railway?**
- **RQ3: Who are the key actors involved in UK railway innovation?**

The purpose of the fourth question is to develop an abstract model of the UK railway innovation landscape building on the descriptive analysis from answering the first three questions.

- **RQ4: Can we create a model of the UK railway innovation system (recognising that it is a complex system) to understand the factors that drive the success or failure of innovation on the UK railway?**

The final, and central, research question focuses on the development of a conceptual framework of how the UK railway innovation landscape ought to be in order to support more innovation that addresses the needs of the UK railway as a whole system.

- **RQ5: Can we develop a conceptual framework, utilising this model, that can enable the more successful introduction of innovation onto the UK railway?**

1.5 Research Approach

The research will use a systems approach to observe and analyse the UK railway landscape, based on the Systems Engineering Process V-model (illustrated in figure 1.7).

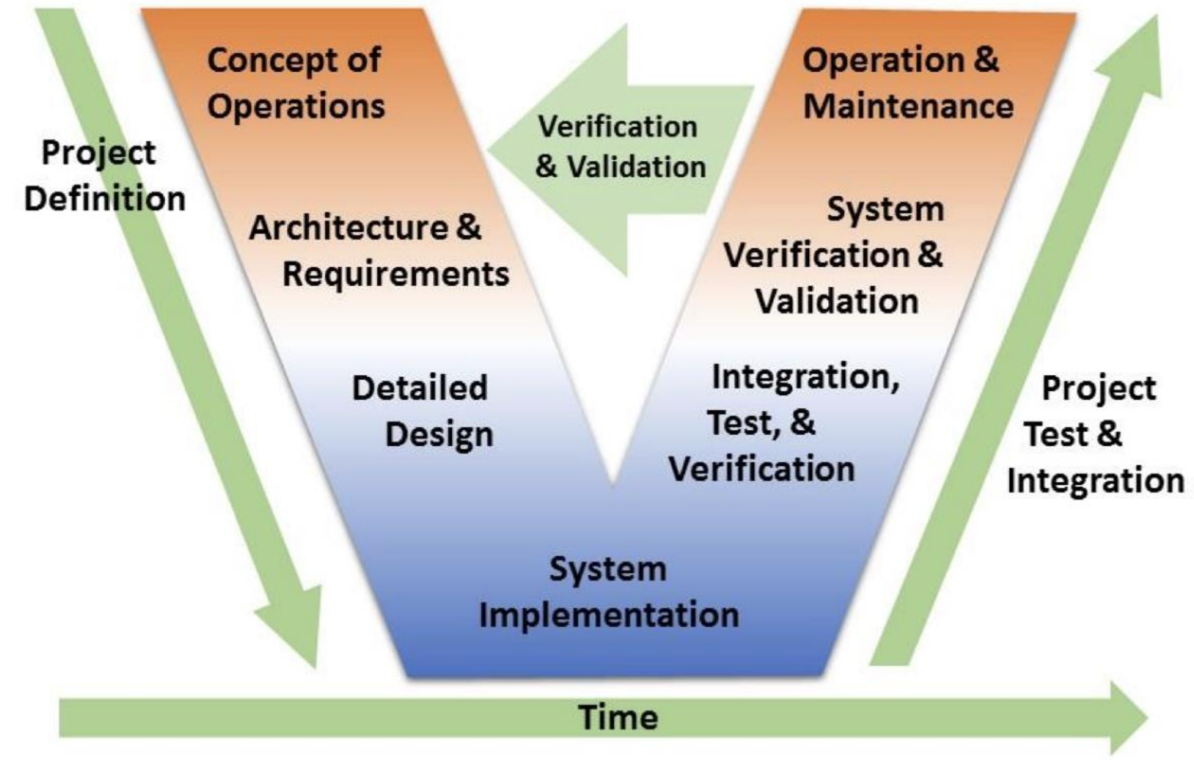

Figure 1.7: Graphical systems engineering 'Vee' model (INCOSE 2015)

For this research, the systems engineering process v-model has been specifically adapted to provide a model for the research approach to this project, this is illustrated in figure 1.8.

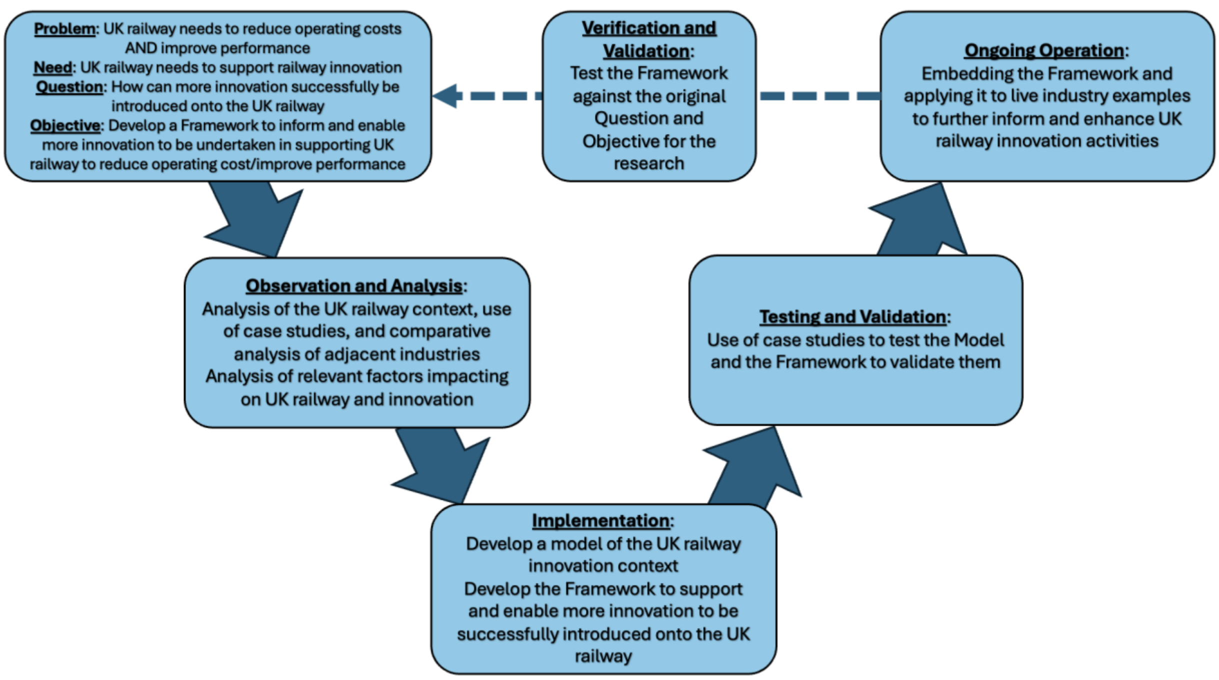

Figure 1.8: adapted v-model to illustrate research approach

This proposed systems approach to the research is based on a constructivist perspective, with the aim to construct a model of the system that can comprehend and explain the system - in this case, the UK railway innovation landscape (INCOSE, 2025).

The research will build on the abstract model of the UK railway to then develop a conceptual framework of the UK railway innovation system to create an optimised approach to introducing innovation onto the UK railway. The objective of this research is to create a framework of how the UK railway innovation landscape could best be to increase the chances of successful development and deployment, to decrease the risks of unsuccessful innovations being pursued, and to deliver the outcomes being sought for railway innovation (ultimately a better railway).

1.6 Structure

The structure of this thesis is set out below:

Chapter 1 – Introduction

In Chapter 1, the background to the research is presented and the problem that the research intends to analyse and address. The objectives for the research are established and the questions that the research seeks to answer are identified. The approach to the research, the scope of the research and the methodology to be used are then described.

Chapter 2 – Literature Review

In Chapter 2, the relevant literature is identified and established to provide the theoretical foundation and knowledge of this research project. Using the existing literature, an analysis is developed to understand theories and models of innovation, the current landscape for innovation in the railway, and identify the barriers and complexities that exist. Building on this analysis, the investigation looks at relevant adjacent industries to rail, to compare the role and complexity of undertaking innovation in those industries and to identify common themes and contrasts.

Chapter 3 – Methodology

In Chapter 3, the problem that the research seeks to address is framed, and then the methodology for the research activities in Chapter 4 is established.

Chapters 4-8 – Observation and Analysis

In these chapters, the detailed research and analysis of the current state of innovation in the UK railway market is undertaken using four separate methods:

- Firstly, by undertaking detailed PESTLE analysis of the factors influencing and impacting UK railway and the role of innovation; in parallel with an assessment of the internal factors that impact the UK railway innovation landscape.
- Secondly, by using an online survey to collect quantitative data for the evidence base.
- Thirdly, by undertaking interviews with a number of key actors to collect qualitative data.
- Fourthly, through analysis of a range of relevant case studies to understand how innovation operates at present and to test those factors identified, referring back to the models of innovation investigated in the literature review.

Taken together, the collected data and evidence will be integrated and analysed using a critical approach to develop a model, that will provide a descriptive analysis of how the UK railway innovation landscape currently operates.

Chapter 9 - Introducing the Framework

In Chapter 9, the model of the UK railway innovation system is used to develop a conceptual framework that sets out how the UK railway innovation landscape could and should be. This framework is designed to build on existing and potential enablers, and mitigate barriers to innovation, to enhance the likelihood of introducing more and better innovations onto the UK railway that can deliver the improvements and outcomes being sought.

Chapter 10 – Testing the Framework

In this chapter, the Framework is tested and validated using several case studies identified in Chapter 7.

Chapter 11 – Verification and Conclusions

In this chapter, the framework and the case study are reviewed, utilising the observations and analysis from the expert interviews, and considering the research objectives and questions. The conclusions from this review are set out and areas for further research are identified to enhance the Framework and our understanding of railway innovation.

The conclusions will focus on developing new knowledge around whether innovation in rail is effective or not, and on whether current investment and organisations involved are effective in delivering innovation for the railway.

1.7 Publications and Background

During this research, an initial paper was presented at the World Congress of Rail Research (WCRR) 2022 setting out preliminary findings, *Introducing the Birmingham Rail Innovation Process: a framework for unlocking innovation in the rail sector* (Burrows, Blumenfeld, Roberts 2022).

In this paper, initial findings from the research project were discussed and the Birmingham Rail Innovation Process (BRIP) – an initial iteration of the UK railway innovation landscape model and theoretical framework - was described. The BRIP was developed as a tool to help explain innovation models and concepts to both the railway industry and university students. This research uses the outputs from the WCRR 2022 paper as a base point to develop the model of the railway and the theoretical framework in chapter 5.

For much of the duration of this research project, the author held the role of Director of Enterprise and Innovation at the University of Birmingham's Centre for Railway Research and Education. During this time, the author led the development of the HydroFLEX project and formed a commercial spin-out company that developed the HydroShunter project (see chapter 7). The author has held several senior roles in the railway and wider transport industry, focused on strategy and innovation, over the last 16 years.

Chapter 2: Literature Review

Chapter Structure

2.1 Introduction

This research is focused on innovation in the UK railway and to develop a framework to enable increased innovation to be introduced onto the UK railway. The literature review is split into three parts:

- In the first part, the literature in the field of innovation models and innovation policy will be discussed.
- In the second part, the literature in the applied field of innovation in rail will be discussed.
- In the third part, the three adjacent transport industries (see chapter 1) will be investigated further.

2.2 Models of Innovation

The development of models of innovation has evolved as the process of innovation has evolved to meet the needs and requirements of modern industry. A useful analysis of this evolution is set out by Rothwell as the five generational steps of the innovation process (Rothwell 1994; Marinova & Phillimore 2003; Nobelius 2004; Berkhout et al 2006).

The first generation is characterised as 'technology push'. This period followed the end of the second world war in a context of the world needing to rebuild and seeing significant technological developments taking place. Societies needed to rebuild and wanted to exploit scientific progress to achieve that, creating the space for supply-driven innovation to take advantage by providing solutions that were wanted and needed.

The second generation of innovation process is characterised by the need for a 'market pull'. This aspect was necessary as the post-war boom slowed down rates, and while prosperity continued, employment growth was not as sustained. In this generation, the demand side now plays a role of stimulating and directing research and innovation.

The third generation of innovation process can be viewed considering the economic conditions that characterised its evolution – economic slowdown, leading to significantly reduced demand, and oil crises, leading to inflation. This model of the innovation process is more sophisticated by recognising the role of actors and their interactions within the process. The intrinsic link between supply and demand is key in the development of this generation, with multiple factors and feedback loops being required to comprehend the process. That link between supply and demand is also characterised by a new focus on linking and balancing potential risks and rewards in analysing the value and benefit of deciding to undertake the innovation process (Nelson & Winter 1977).

The fourth generation of innovation process developed during the period of return to economic growth in the 1980s. The pace and efficiency of product development characterises this generation of the innovation process, with learning from Japanese industrial innovation strategies leading the way, in particular their focus on: (i) parallel development activities to accelerate the process; and (ii) the need to integrate suppliers into the development process to develop a final, ready-to-commercialise product to manufacture as efficiently as possible at market entry.

The fifth generation of innovation process focuses on the pace of development, the use of lean principles, and timely delivery of new product to market - in the context of a period of rapid technological development and globalisation, the need to be able to innovate at pace is essential. This context creates a need for organisations to expand their networks and collaborate, to be able to pool the resource required to invest in successful R&D activities. Figure 2.1 illustrates these five generations in summary.

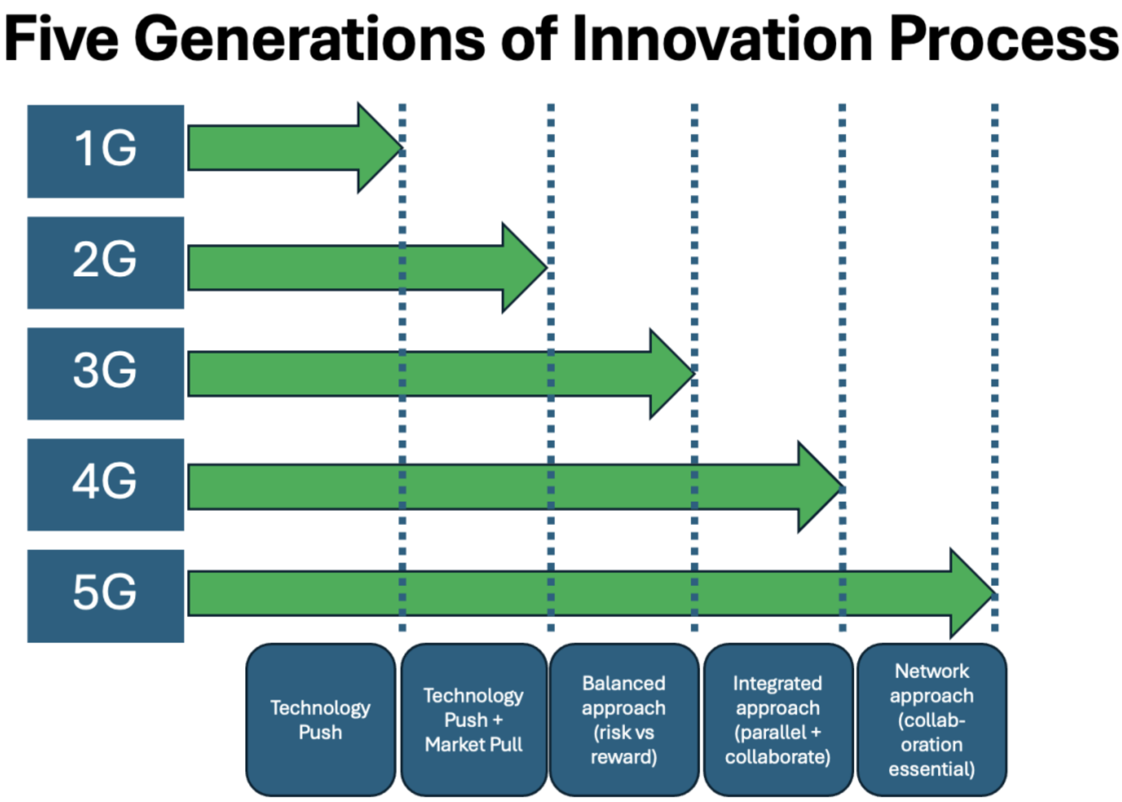

Figure 2.1 Summary of Rothwell's five generations of innovation process

The five generations of innovation process, as set out by Rothwell, have been further developed (Marinova & Phillimore 2003) to go beyond the descriptive analysis and pure commercial application, and to look at these conceptual approaches to the innovation process as applied in all contexts (Meissner & Kotsemir 2016).

Looking beyond the process alone, this approach of analysing generations of innovation models can be characterised in the following steps:

Firstly, the 'technology push' process can be characterised as the 'black box' model of innovation which can be simply described as resource inputs (money and effort) will generate new products as outputs from the black box of innovation.

Secondly, the role of market demand for innovation can be characterised as the development of linear models of innovation, whereby innovation happens in a step-by-step process. We can consider this as the process of moving through the Technology Readiness Levels, as shown in figure 2.2.

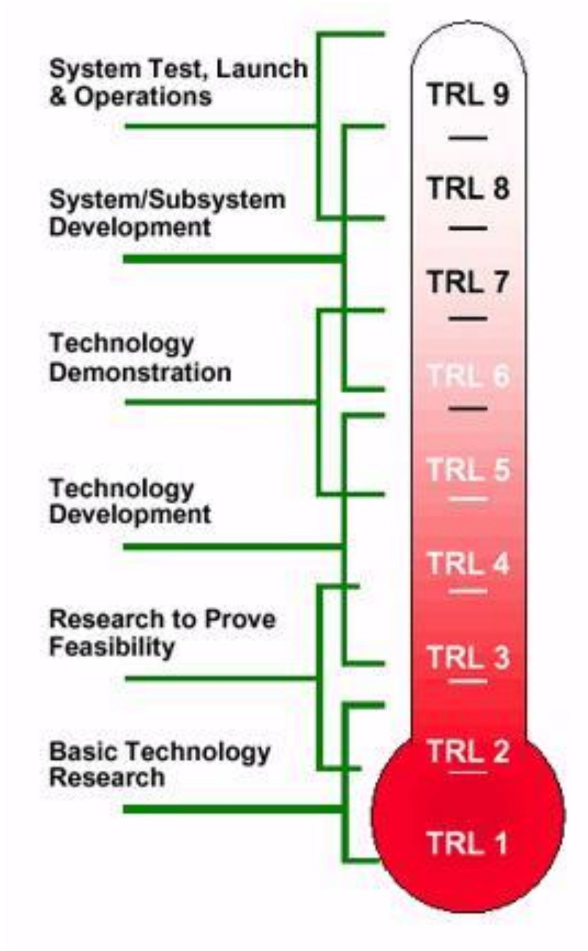

Figure 2.2: Technology Readiness Levels (European Space Agency)

Thirdly, Rothwell's interactive or coupling model, which brings together supply and demand considerations as key factors in the innovation process, is characterised as the generation of interactive models where the role of actors in a much more complex environment is factored in.

The fourth generation of the innovation process that highlighted the roles of supplier integration and collaboration, is characterised as the generation of systems models. This generation investigates the role of networks in powering innovation activities and the role of a wider set of actors in influencing and enabling innovation.

The fifth generation of innovation process that Rothwell reached is the network approach. Marinova and Phillimore characterise this generation as evolutionary models of innovation, reflecting the use of biological rather than mechanical metaphors to more accurately describe how innovation happens within the context of a dynamic environment with large numbers of actors potentially influencing the success of innovation (Marinova & Phillimore 2003).

A sixth generation of innovation model is also proposed, the innovation milieux, that reflects a place-based context for innovation to happen. This reflects thinking developed in the fourth and fifth generations around the roles and influence of actors and networks, in particular clusters of activity focused on a particular area (such as the railway for example).

These analyses of generations of innovation processes and models are informative in both understanding and characterising key factors used to comprehend and explain innovation activity.

Building on this review of the development of models of innovation, this section investigates several specific models of innovation. To begin, the research investigates three models of innovation – open innovation, mission-oriented innovation, and the multi-level perspective. Further relevant examples from literature are then investigated to support and augment the learning.

2.2.1 Open Innovation

Open innovation is a relatively recent theoretical approach to explaining innovation that contrasts with traditional innovation models that emphasise a 'closed' approach to understanding innovation activity within an organisation (Chesbrough 2003). Open innovation focuses on the opportunity of making use of all available knowledge to an organisation to undertake innovation - not only those capabilities available from within the organisation but taking advantage of collaboration to use external ideas. By focusing on the value of the knowledge and capabilities that are relevant to delivering innovation, it is apparent that such capacity is bound to be more widely available across a much larger network of actors beyond an individual organisation.

At the heart of the model of open innovation revolves is the idea that in a world of widely distributed knowledge, companies cannot afford to rely entirely on their own research and capability but must also acquire external knowledge and develop their internal ideas utilising collaboration with external actors (Chesbrough 2003; Chesbrough & Bogers 2014). This could include buying-in expertise, resources, or technologies, as well as utilising different operating models beyond a standard in-house approach of product design, development, and deployment such as partnerships or joint ventures. The many benefits of open innovation for companies therefore include access to a greater pool of knowledge and talent, increased access to potentially exploitable ideas and to a greater number of innovations (Enkel, Gassmann, Chesbrough, 2009) and being able to draw on the deep technical knowledge of external organisations, including universities, to enable innovation to take place (Laursen & Salter, 2006).

As discussed above, a key element of the fifth generation of the innovation process is the need for pace in a time of rapid technological advances, that requires organisations to collaborate to be able to be innovative, and to reduce time for product development to market entry, and therefore remain competitive (Enkel, Gassmann, Chesbrough 2009).

Fundamental to the open innovation model is the openness aspect - that an organisation gets more benefit by relinquishing a certain amount of control of the innovation process to get more value from the outcome of it. By being more open to additional ideas a range of benefits also become available in doing innovation such as reducing costs and risk, as well as increasing creativity and pace (Chesbrough 2003).

By using the model of open innovation, organisations can better exploit knowledge and ideas from both within their own organisation as well as from the wider landscape. It can also increase the possibilities for an organisation to make better use of their own products and capabilities by being more open to collaboration with other organisations. This *outside-in approach* (Enkel, Gassmann, Chesbrough 2009) places value on both knowledge and its importance for innovativeness, and the importance of innovation networks to use collaboration to gain competitive advantage.

Through a more collaborative approach to innovation, organisations can also be more open to more effectively realising benefits from their activities beyond the traditional measure of selling products or services, through exploiting intellectual property either internally (by broadening the range of commercial activities to exploit their knowledge) or externally (by licensing intellectual property to partners to further exploit). This *inside-out approach* (Enkel, Gassmann, Chesbrough 2009) allows the knowledge and innovation outputs to be exploited more effectively and efficiently by placing the market activity (the selling) in the responsibility of organisations with the business models and infrastructure to best exploit it.

The table below summarises open innovation versus closed innovation, and the two approaches to open innovation discussed above.

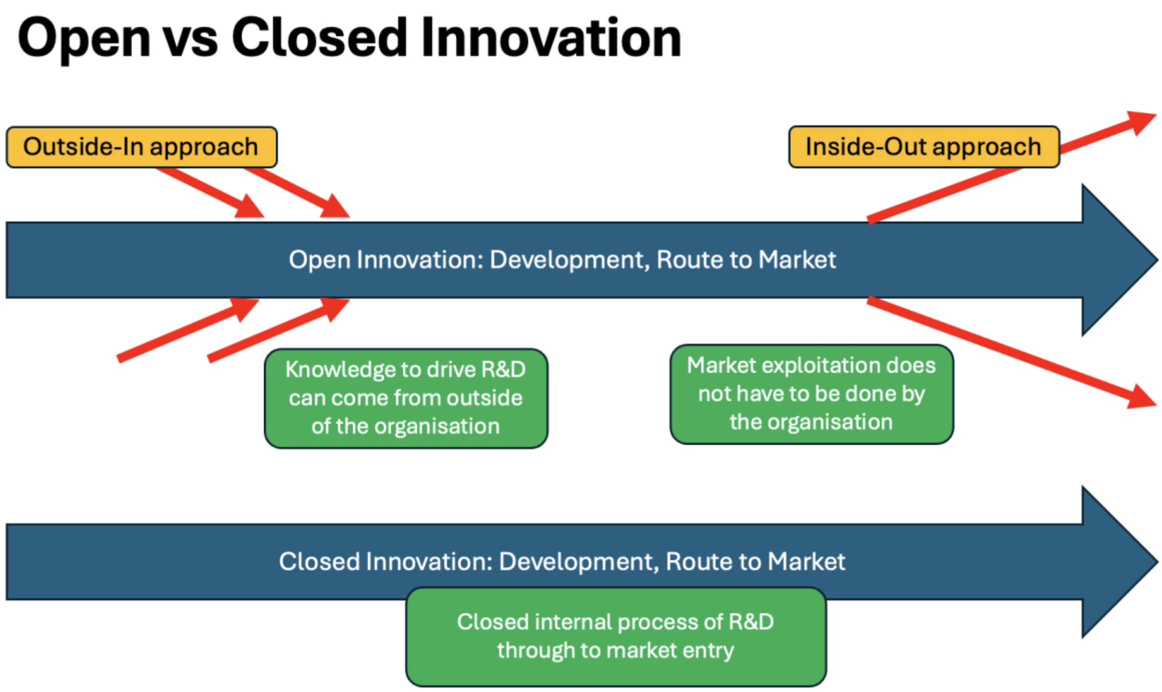

Figure 2.3: Summary of open vs closed models of innovation

Open innovation requires organisations to continuously adapt and evolve their innovation processes in response to evolving market conditions and technological advancements. This requires an awareness of the need to have a range of dynamic capabilities that can identify potential opportunities and how to manage their development and exploitation. These organisational requirements have been categorised as: (i) open technology sourcing, (ii) open mass innovation, and (iii) open collaborative innovation (Podmetina et al 2018).

The model of open innovation also requires an understanding of how the actual activity generates value opportunities for the organisations taking part. The two approaches of outside-in and inside-out demonstrate the value of knowledge as an input into the innovation process (for outside-in) and the value of licensing the outputs from the innovation process to the user/exploiter of the innovation output (for inside-out). These roles are alien in the closed concept of innovation process but are key in understanding the gains available by collaborating in an open innovation process (Chesbrough, Lettl, Ritter 2018).

The counterpoint to these opportunities of adopting open innovation as a model is that an organisation will need to develop a range of additional skills to manage potential challenges from open innovation (Podmetina et al 2018). These include effectively managing collaborations, ensuring alignment with partners (such as incentives and objectives), protecting intellectual property rights, while also ensuring that traditional perspectives around openness and risk are overcome.

The model of open innovation is extremely attractive. It focuses on the importance of outcomes from innovation – why are we seeking to innovate in the first place? Open innovation is a model informs an understanding of how innovation can be done more effectively to develop better solutions that can utilise knowledge and technology more effectively to deliver improved outcomes.

2.2.2 Mission-Oriented Innovation

Mission-oriented innovation is a model of innovation that looks at the fundamental purpose of innovation and how to utilise that within a public policy context. The model of mission-oriented innovation focuses on the purpose of innovation – and the role of governmental bodies to identify significant challenges that require a focused mission to address them (Mazzucato 2018; Janssen et al 2021). Mission-oriented innovation explains innovation from the perspective of the end-user and beneficiary as governmental bodies and wider society, seeking to utilise innovation to answer the major problems that public policy seeks to address – which are at the scale of global mega-challenges such as tackling climate change, eradicating diseases, and ending global poverty.

By identifying these grand challenges as a key purpose for innovation, we can better incorporate the motivations of actors into the activity of innovation. Mission-oriented innovation provides the opportunity for transformative innovation policy (Diercks et al, 2019) to generate motivations and incentives to undertake innovation to deliver solutions to major social and environmental challenges.

In this way we can see innovation policy as a means to an end in supporting the delivery of social, economic and environmental policy agendas (Diercks et al, 2019). An attraction of mission-oriented innovation is a model is that we look at innovation through the prism of what it can achieve as an outcome, rather than at the technology or the process of doing innovation. Innovation is frequently seen as a technical process of improving products and services without reference to the purpose of why this is being done – for example, the black box of innovation activity, or the process of working through the technological readiness levels to produce supply-side driven (i.e. the first and second generations of innovation process as discussed above). This leaves a gap in our understanding of why we might be doing this for any reasons beyond purely technological and/or commercial benefit.

The model of mission-oriented innovation places governmental bodies as having a critical role in driving innovation by setting ambitions missions that act as the need for innovators to target. For organisations looking to innovate, these missions provide major targets on a scale that generates significant ambitions for the supply of innovation. Where the model of open innovation is a bottom-up approach with innovators supplying potential solutions to problems, mission-oriented innovation is a top-down model with public policy objectives driving demand for innovative solutions (Mazzucato 2018; Hekkert et al 2020). Such a top-down model provides strategic focus for the utilisation of innovation resource and capacity to solve the major challenges that exist.

Key to the use of missions as a model for innovation is the proactive role of governments in investing in and supporting innovation. They need to be driving the demand for creative solutions that can have an impact on addressing the identified missions (Mazzucato 2018; Janssen et al 2021). Like the model of open innovation, mission-oriented innovation places emphasis on the need for collaboration – not just between innovative organisations though, but also across all relevant stakeholders from governments and other bodies with an interest in the mission.

Mission-oriented innovation is a policy-driven model of innovation, and therefore demand side-led, targeting transformations to social, economic, and environmental policy issues (Hekkert et al 2020). The model of mission-oriented innovation relies on proactive governments defining these missions and establishing the motives and incentives for organisations to take part. This involves setting achievable, measurable, and ambitious targets and making sufficient resource available to incentivise action from innovators. The mission-oriented model gives innovation a critical role in the public policy agenda as a means of delivering significant impact to address the major challenges that cut across multiple policy areas. But mission theory's model of innovation is inherently political and top-down (Janssen et al 2021) which provides a useful insight on a part of innovation theoretically but does not paint the full picture.

An evolution of the policy-driven model is the mission innovation system framework (Hekkert et al 2020). The mission innovation system focuses on the network of actors who can play a role in the development and implementation of innovative solutions (i.e. supply side plus demand side) that can address the original mission from the policy (demand) perspective (Hekkert et al 2020).

The mission innovation model complements open innovation as an alternative theory for describing and understanding innovation. Mission-oriented innovation focuses on the role of innovation demand (i.e. the user) to incentivise innovation to happen to address major challenges; this contrasts with open innovation that focuses on the role of innovation supply (i.e. the innovator) to deliver better outcomes.

2.2.3 Multi-Level Perspective

Where the model of open innovation seeks to explain innovation from the individual innovator perspective, and the model of mission-oriented innovation explains innovation from a demand perspective focused on outcomes, there is a third model of innovation that provides a theoretical framework in the context of the systemic change driven by an innovation.

The multi-level perspective provides an explanation of technological change (i.e. the process of seeing innovations develop and become deployed) through an analysis at three different levels (Kemp 1994; Geels 2002). These levels are different aspects of technological and social systems that provide the space and context for innovations to take place. Of particular interest and relevance is that this is another model of innovation that focuses on both the technical and social aspects of innovation (Geels 2012).

Firstly, there are the niches which are the smallest of the levels and can be characterised as emerging areas for new ideas and technologies to be developed and deployed. They are often described in the context of areas to address environmental issues with novel technologies (Geels 2004). We can understand niches as spaces which are more open to novel ideas, processes, technologies, and business models – usually as the space to address major challenges more creatively and could be characterised as more disruptive than incremental.

Secondly, there are the regimes which are the established socio-technological norms and structures in their own sectors or industries. We can understand the regimes as being the status quo and the current state of the art, using technologies and processes that are well-established and understood by most actors in that sector or industry (Nelson & Winter 1977; Rip & Kemp 1998). As such, they fundamentally differ from niches by having the existing technologies and processes being locked into place as the normal way of doing things, thereby acting as a barrier to innovation as opposed to having an openness to new ideas and practices (Geels 2012).

Additionally, from a social perspective, the regimes can be seen as being managed and controlled by a range of actors and interests that will inherently want to maintain their positions of relative strength. As a result, the regimes will be underpinned by a complex network of actors, institutions, regulation, standards, and norms that maintain and protect the status quo thereby acting as a barrier to change and to innovation (van den Ende and Kemp 1999; Rip & Kemp 1998).

These barriers to technical change are important and are relevant to the UK railway innovation landscape (see later in this chapter). As Geels notes, "*cognitive routines make engineers and designers look in particular directions and not in others*" (Geels 2004, p.910); cognitive rules are well-understood and regularly used skills and competencies that are established in the socio-technical regime. Any threat of innovations that can nullify these rules and make them redundant will not be welcomed while the existing regime is considered sufficient in solving problems and meeting user needs (Kemp 1994; Rip & Kemp 1998).

The third and broadest level of analysis are the landscapes which are the bigger context within which we find the niches and regimes. The landscapes represent the bigger picture comprising governments, mega-trends (such as climate change, urbanisation etc), external events (such as global pandemics and wars), and all the other elements that can have an impact on regimes and niches from outside (Geels 2011).

Landscapes can be shifted by external factors in dramatic ways that see norms being reshaped in a paradigm shift creating the space and requirement for a technological shift (Geels 2002). For example, the identification of climate change as a critical global challenge that needs addressing can shift political narratives suddenly and significantly, thereby having a major impact on the norms many individual socio-technical regimes, such as the rail industry.

It is a feature of the multi-level perspective that landscapes, regimes, and niches, can all co-evolve with paradigm shifts in the landscape causing changes in the socio-technical regimes and in related niches; while the emergence of niche innovations can develop changes in regimes and in turn reshape the wider landscape. However, the opportunities for radical innovations breaking out from niche opportunities to wider application requires shifts in either the regime or the landscape to drive the demand opportunity for them (Geels 2002).

The multi-level perspective provides a framework for what it calls technological transitions which sees a shift in the technological status quo with the adoption and acceptance of innovative products and solutions (Geels 2002). These technological transitions see radical innovations developing in the niches and attempting to emerge to challenge the dominance of the status quo in socio-technical regimes. The technological transitions can be enabled or stifled through public policy interventions and through the role of relevant actors to accelerate (or block) innovation. Generally, the prevailing landscape can enable innovations to break through and gain acceptance where they put pressure on the regime by providing the need for the innovation in one of two ways: (i) slowly developing / long-term trends such as population growth and urbanisation, or (ii) exogenous shocks such as wars, political upheavals, or pandemics.

The multi-level perspective is a valuable theoretical framework for understanding the roles of actors within the system of innovation (Geels 2004). This perspective provides a model that enables research to look at the system as a whole and comprehend the roles and interactions of actors, knowledge, technology, politics, and society, providing a view across the breadth of the system under investigation (Geels 2012).

Figure 2.4 sets out a summary of the Multi-Level Perspective, demonstrating the methodology for explaining how innovations can break through and become normalised in a socio-technical regime such as the UK railway.

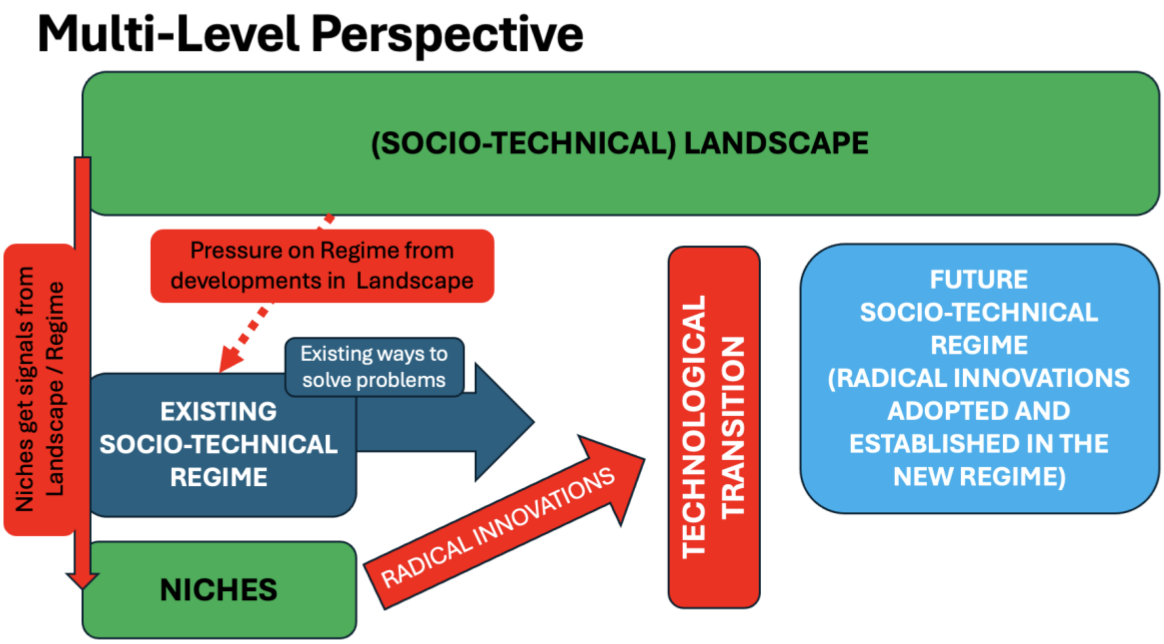

Figure 2.4: summary of the Multi-Level Perspective framework, adapted from diagram in Geels 2012

This model for innovation complements the open and mission-oriented models of innovation. The multi-level perspective framework takes the opportunities of the other two models and places them into the context of doing innovation. It provides an analysis of both the technological and social contexts that are equally important in understanding how innovation happens.

2.2.4 Other useful learnings from theories of innovation

There are several theories of innovation that can provide additional learning to this research.

Joseph Schumpeter and Creative Destruction

Firstly, the theory of innovation put forward by Schumpeter that focuses on the importance of entrepreneurs and disruptive innovations in driving economic growth. Schumpeter describes the role of 'creative destruction' (Schumpeter 1942) which can be viewed as similar to the technological transitions set out within the Multi-Level Perspective theory investigated above. Of relevance is his recognition of the importance of both technological advances and of institutions in understanding how innovation happens and breaks through (Schumpeter 1942). As an economist, Schumpeter sees innovations as disrupting the equilibrium of the current economic system and therefore their potential as key drivers of economic growth. This is due to the constant evolution of economies, with the context of the economy (i.e. the time and the place) being relevant to the state of the system – with markets emerging, product needs and requirements shifting, and new technologies appearing.

These innovations breakthrough in cycles with waves of innovation bringing forth the creative destruction that breaks the equilibrium of the economic system; the periods in-between are characterised by consolidation and a reorganising of the economy to adapt to these changes and establish a new equilibrium. The parallel with a technological transition shifting a socio-technical regime from an old technology to the adoption of an innovation from the MLP is clear.

To that end, he connects political institutions and public policy as partners in the valid role of using innovation policy to drive economic growth, as they are directly comparable with political entrepreneurs looking for policy innovations to gain political success through voter approval (Hospers 2005).

Neo-Schumpeterian theories of innovation

Building on Schumpeter's work are Neo-Schumpeterian theories of innovation – an early example is the work of Schmookler who argued that innovation is generally demand-led, based on capital investment into technologies or industries that led to clusters of patents being registered – as investment in innovation matches economic (market) opportunity to justify the investment (Schmookler 1962). This demand-led, 'market pull' theory of innovation can be characterised as a second-generation model of the innovation process and has been criticised for focusing solely on that single direction rather than considering the bi-directional balanced approach of both technology push and market pull (for example, Kleinknecht & Verspagen 1990).

Leading neo-Schumpeterian theories that this research is interested in are the related theories of innovation systems and evolutionary growth.

Innovation systems theory emphasises the importance of systems in developing and building momentum behind technological advances due to the system of actors involved and their interactions (such as companies, universities, government bodies) (Lundvall 2016). Innovation is seen as a constantly evolving, cumulative process of development that can move at varying speeds (Lundvall 1992). Innovation systems are made up of actors, institutions, and networks, that together play a role in the development and diffusion of new products and processes (i.e. innovations) (Bergek et al 2008).

The study of national innovation systems which sets out how technological advances are driven by the interactions between several key actors such as firms, universities, government bodies and these interactions are facilitated or guided by public policy and investment (Nelson 2000). While this theory is labelled national systems of innovation, it fully recognises the impact of globalised markets and international corporations increasingly blurring those boundaries (Lundvall 1992).

Regional systems of innovation is another place-based model for innovation (for example, Porter 1996) that focuses on the role and position of firms in driving innovation and their proximity to each other to provide agglomeration and clustering benefits providing innovation drivers

Key to this model of innovation systems is the importance of the relationships and interactions between institutions and organisations as a key driver in the innovation process. There is a strong emphasis on the role of institutions, policies, and regulatory frameworks in shaping innovation outcomes. Institutions provide the framework (rules, incentives, norms) that influences the behaviours of actors within innovation systems, influencing decisions about investment, research priorities, and knowledge sharing. Institutions are judged as being critical in enabling an environment that allows innovation and removes barriers to change.

Evolutionary growth theory is complementary to innovation systems theory, focusing on the knowledge and learning required as part of the innovation process and particularly how the present institutions have a key role in adopting new technologies and integrating them into current practices (Nelson 2005). Its central premise is that technology advances in an evolutionary manner as it is shaped by the inputs and institutions that drive both its need and knowledge required, and by the outputs it generates including its impacts on those institutions that shaped it.

Evolutionary growth theory builds on the technological regimes that are characterised by the established routines and knowledge that can influence and shape technological development. A focus for research in this field is on the importance of learning new processes and knowledge to adapt to, and adopt, innovations which can then drive economic growth (Freeman 1991).

The theories of innovation systems and evolutionary growth both look at innovation from a broader social and economic perspective. By going back to the earlier discussion of a closed system of innovation (which was contrasted with the open innovation model), we can contrast that perspective which focuses on a singular technological process of development within a single organisation, with these much wider models that place innovation within the wider context and system of actors and institutions.

Two further variations of innovation systems theory are:

- The study of sectoral systems of innovation which focus on systems relating to a particular industrial sector - which is particularly relevant to this research looking at UK railway innovation (Malerba 2002).
- The study of technological systems of innovation which are focused on systems relating to a particular technology (Carlsson & Stankiewicz 1991).

These related theories of innovation systems all emphasise the role of actors and institutions, as well as public policy, in steering and enabling innovation systems to succeed along with the importance of creating effective interactions between the appropriate actors to support collaboration, investment, learning and, ultimately, the adoption and diffusion of innovations.

They also emphasise the roles of actors and institutions in creating technological paradigms or regimes, where the state of the art is established for a period of time in a particular and appropriate context. That technological paradigm can be incrementally improved, or it could be subject to a Schumpeterian moment of creative destruction by the introduction of a radical innovation, that sees a technological transition deliver an advance in the technological state of the art.

Constructivist theory

One final theory of innovation to discuss is that of the social construction of technology. This theory argues that technology is driven by human action and not the other way round and that the adoption of technological advances and how technologies are used and understood can only come from, and be directed by, human knowledge and action (Pinch and Bijker 1984).

Of particular interest to this research is the statement of intent from social constructivists to 'open the black box' of technology (Bijker, Hughes, and Pinch 1987) where technological innovation follows a closed model of technological development inside a black box remote from its real-life context and environment.

This builds from social construction theory (Berger and Luckmann 1966) that society creates and institutionalises roles, thereby creating a constructed social reality that is learnt and then played by all actors involved within a set of normative rules. Therefore, our social reality is subjective and formed through learning social and cultural knowledge by experience of habits, customs, and institutions.

Hughes expresses the theory as seeing technology as a form of creativity, being developed to solve current problems in a world that has been built and cultivated by humans (Hughes 2004).

The social construction theory of technology sees innovations emerging as an output of the interactions between firms, organisations, institutions, and the other actors within a network (Bijker, Hughes, and Pinch 1987). This network is a key part of the innovation process, providing a technology complex of wider expertise to enhance and promote the understanding and acceptance of the innovation, as well as its development. This enhances our understanding of innovation as an activity that incorporates much more than solely the practical development of a solution in itself. It requires the contextual analysis of being able to successfully place the innovation into the context to appreciate its real value in solving a contemporary problem.

This theory goes a step further than innovation systems theory in that the actual technology plays a lesser role than the interactions in terms of what the actual innovation output is.

This theory is much more effective at drawing out the roles of actors in innovation systems, rather than the technological innovation itself.

2.2.5 Summary of learning from models of innovation

This section has established a theoretical basis for understanding models of innovation and how we can use them to understand the role and application of innovation to an industrial context. These theories of innovation reflect a variety of perspectives on how innovation happens, how it is organised and enabled, as well as reflecting on the purpose and outcomes of doing innovation.

Table 2.1 sets out a summary of the models of innovation investigated in this literature review with the key learnings.

Models of Innovation	**Key Themes**
Open Innovation	Value of collaboration and focus on maximising access and utilisation of knowledge and capability to develop and exploit innovation. Importance of considering the respective supply and demand side roles.
Mission-Oriented Innovation	Motivating and incentivising innovation to address grand challenges, using public policy as an instrument to drive innovation. A useful example to consider for mission innovation is NASA and the focus on putting a man on the moon in 1969 - a grand challenge was used to focus efforts and resource on a clearly identifiable goal.
Multi-Level Perspective	The respective roles of, and interactions between, the Niches, Regimes, and Landscapes to understand established socio-technical regimes and technological transitions.
Schumpeter	Cycles of disruptive innovation. A useful example of these cycles that might be considered are how our access to

	recorded music has evolved over the last four decades – moving from vinyl records, to cassettes, to compact discs, to mini-discs, to MP3, and now to streaming. All of these evolutions have not been incremental but transformational, making the previous technology obsolete.
Neo-Schumpeter (Innovation Systems)	The fundamental importance of recognising the roles of actors and institutions in wider systems of innovation. Evolutionary, ongoing process of innovation.
Social Construction	Innovation as a resulting output from interactions between actors and institutions. Innovation develops within a network and gains acceptance thanks to the efforts of that wider network.

Table 2.1 Summary of models of innovation considered in this research review

The key learnings from the literature that this research will build on include:

- The importance of considering the roles of the supply and demand sides in enabling successful innovation to happen.
- Viewing innovation in a cyclical rather than linear manner. If we consider the multi-layer perspective as a means of understanding how technological advances happen, then the role of niches in developing radical innovations that are encouraged from signals sent from the landscape and regime to provide the technological transitions that pull improvements into the state of the art.
- Innovation as waves or cycles of improvement that build on the existing landscape and technological norms. In this context, innovation is about constant cycles of improvements to derive benefits rather than a linear process with a start and an end point.
- Understanding the fundamental roles of actors and institutions in guiding and influencing the innovation process. Understanding the model of innovation is considerably more sophisticated than a mechanistic process of technological development alone.

- Developing the perspective of three levels guiding and influencing the process of innovation – the landscape (the context for the innovation to develop), the development (the actual identification through to completion of the potential innovation), and the outcomes (the delivery of the innovation to the market which then shifts the landscape through an improvement to the state of the art).

In the next section, the learning from the literature will be applied to the context of the UK railway.

2.3 Innovation in the rail industry

In this section, the research seeks to understand how innovation happens in the UK railway industry. As discussed in Chapter 1, the UK railway is frequently found to be lacking in making use of innovation. However, this has not always been the case, and this research seeks to understand how and why this has changed.

Following an investigation of the experience in the UK, the research then looks at international experiences to provide a fuller understanding of the innovation landscape across global railway systems.

In this section, the research is informed by the Schumpeterian theory of innovation which uses cycles of rapid technological development, enabled by clusters of innovation, to drive economic growth (Schumpeter 1942, Ayres 1990, Thompson 1990) – this theoretical approach will be used as an analogy. This analogy is helpful in defining broad periods where the UK railway has been transformed by the application of new technologies and processes.

2.3.1 The UK context

The coming of the railway

The opening of the Stockton and Darlington Railway in 1825 (ICE website), followed by the opening of the Liverpool to Manchester Railway in 1830 (ICE website), established the coming of the railway age in the UK and, indeed, globally.

The market success of the Liverpool to Manchester railway led to the growth of 'Railway Mania' where huge numbers of people rushed to invest in this new technology (Odlyzko 2010). This immediately established the significant demand for the railway as a completely innovative transport system – and this demand driving the supply of innovation i.e. new railways. This demand was catered for by several rapidly established railway companies, all in direct competition with each other. Although the railway was a new technology, within only a few decades many railway companies had established their own laboratories to undertake research and innovation activity in support the engineering departments of the railway company (Gilchrist 2009).

As the railway network rapidly grew across the UK through the course of the 19th century, the application of this new transport technology became increasingly inefficient with far more railway network than was reasonably required due to two factors – excessive competition between the private railway operators, and a failure by the UK Government to effectively regulate the railway as it had developed (Casson 2009).

The age of electrification

The application and impact of electrification technologies on the railway has been a long, ongoing process. From a theoretical perspective, we can view this area as one where the technological advance has brought about a family or cluster of innovations for specific railway application where the technical bonds applied to the specific industrial sector make this a case of long-term diffusion of the technological innovation (Clark, Freeman, Soete 1981).

The development of electrification technologies for railway applications took place in the mid-late 19th century with the practical introduction into operation of electric traction power in 1881 in Germany (Guinness Book of World Records) and in the UK at the Volks Railway in Brighton in 1883 (Volks Railway). However, by 1939 only London Passenger Transport and the Southern Railway had applied electrification to any significant scale (Aldcroft 1969).

While the modus operandi of the large railway companies, with their own internal laboratories established to support their engineering divisions, would appear to demonstrate the closed model of innovation as a purely internal process for each railway company, there is firm evidence of railway engineers sharing knowledge through their membership of learned institutions and publishing papers, as well as sharing ideas and personnel with universities and their peer networks (Divall 2006).

With the nationalisation of the railways in 1947, there was a clear opportunity for improved coordination, regulation, and investment to start the rebuilding of the UK railway. The railway laboratories were brought together as a Research Department for British Railways (Gilchrist 2009).

While the railway invested significantly in research to enable modernisation of operations to reduce cost and increase performance and efficiency, it was not necessarily a rapid adopter of the latest technology. The 1955 Modernisation Plan brought significant investment in electrification of the mainline railway network and the replacement of steam with electric and diesel trains (Cox 1957). However, it was only in the 1960s that diesel and electric traction power systems were introduced at a significant scale, even though they were proven technologies, having been in widespread use across the world for more than two decades – including in the UK. But the transition away from steam - which could have been achieved significantly before the mid-1960s when it finally happened – was hampered by the fact that steam power was locked into the mindset of the rail industry for many reasons including familiarity with existing technologies - steam provided the technological basis for the railway - to adopt electric and diesel technologies required a wholesale shift in technology and mindset. (Aldcroft 1969).

These examples illustrate that although innovation has played a significant and recognised role in the UK railway, it has not always been immediately welcomed and deployed.

Privatisation

The latter decades of the 20th century saw a fundamental shift in the UK railway with innovation in both the technological context as well as the operational context with the introduction of privatisation to the UK railway.

From a technological perspective, the UK railway had benefited from a centralised research and innovation programme led by the British Railways Research Division and a Joint Programme, funded by British Railways and the UK Ministry of Transport. The Joint Programme had attracted funding from the Ministry to support a strategic research objective for high-speed ground transportation (Gilchrist 2009) demonstrating a policy demand that illustrates the mission-oriented theory of innovation discussed earlier in this chapter.

As the Research Division was a part of British Railways, it was driven by demand from the operational divisions of the UK railway and its specific needs for support and improvement. This direct connection between innovation supply and demand in the UK railway innovation landscape lasted until 1996 when British Rail Research was sold to a private company, thereby removing that direct institutional link for the first time in the UK railway's history. It is interesting to note that railway productivity in the UK significantly improved and was remarkably high in the run-up to privatisation between 1975 and 1995 - a period that saw the UK railway outperform its European counterparts (Bagwell 2004).

<u>Rapid technological advances (21st century)</u>

Digital technologies are not new but the technological advances that digitalisation is enabling are significant and the first two decades of the 21st century have seen major steps being taken – cloud computing, big data analytics, artificial intelligence, robotics and automation, and several others that can all play a role in the railway environment. At the time of writing, we are in an innovation cycle for the railway that could and should see a significant adoption of digital technologies to deliver a competitive, efficient, reliable, and sustainable railway (Steele & Roberts 2022).

The development and adoption of digital signalling, traffic management systems, and automatic train operation, onto the railway is delivering tangible change to railway operations (for example, the deployment of Automatic Train Operation enabling 24 trains per hour to use the Central London Thameslink route; Railway Gazette International 2018). While customers are quickly becoming accustomed to using digital services providing ticketing and real-time information as a minimum expectation.

UK rail supply industry

The UK rail supply industry is a significant industrial sector, making an estimated annual economic contribution of £17.8bn to the UK economy, £6.2bn of tax revenues, and supporting 317,000 jobs directly and indirectly (Oxford Economics 2021).

The rail supply industry comprises rolling stock manufacturers, infrastructure, equipment, and services providers, as well as the rolling stock owning companies, universities, trade associations, and other supporting entities – a broad spectrum of organisations with a breadth of solutions and capabilities that can be rail-specific or applied across multiple sectors. The rail supply industry is, generally, the source of innovation supply onto the railway (the UK railway operations industry can generate or directly source some innovation supply but, in general, the supply industry is the primary source).

The rail supply industry is a competitive marketplace with major international players at the top of the chain including Original Equipment Manufacturers such as Alstom, Siemens, and Hitachi, and Tier 1 infrastructure contractors such as Balfour Beatty, Vinci, and Skanska; and a much larger number of Small and Medium sized Enterprises feeding into the sector at various levels across the supply chain.

One significant structural initiative from the rail supply industry was the establishment of the UK Rail Research and Innovation Network (UKRRIN). In 2018 a group of universities, led by the University of Birmingham, partnered with a group of industry organisations (combining of OEMs, Tier 1s, SMEs, the Rail Safety & Standards Board, the Railway Industry Association, Network Rail, Transport for London, and High Speed 2 Ltd) to establish UKRRIN with the express aim of building a collaborative network across industry and academia to foster and enable collaboration in railway research and innovation. The clear ambition was to establish a network of partners to enable the development, adoption, and diffusion of innovation into the industry more effectively. UKRRIN followed in the footsteps of the Rail

Research UK Association (RRUKA) and incorporated its role as a convenor and coordinator of rail R&D activity, but with a stronger focus on industry partnerships and accelerated commercialisation of research and development activities (Dobell 2017). RRUKA in turn was a successor to the Advanced Railway Research Centre that had been set up at the University of Sheffield by the British Railways Board to take over the coordination of British Railways research and move it into academia alongside offering industry training and development (Smith 1997).

The development of UKRRIN was a direct response to a specific request from the rail supply industry and government to establish such a network that could enable and accelerate industrial research, development and innovation, as well as the skills required to support this, to meet the industry's ambition to prioritise innovation (Rail Supply Group 2016).

UK rail operating industry

The UK operating industry comprises passenger and freight operating companies and the infrastructure managers. The passenger train operating companies are a mix of operators that are already publicly owned at the time of writing, and privately-owned companies operating under National Rail Contracts with the Department for Transport. These private companies will over the next couple of years move into public ownership as well and come within Great British Railways.

Network Rail is the owner and manager of nearly all of the UK railway infrastructure network. Network Rail will also be brought into Great British Railways in the near future. High Speed 1 is privately-owned infrastructure, and the intention is for both High Speed 2 and East West Rail, when they are delivered, to use the same model as well.

The Freight Operating Companies are privately owned, and, unlike passenger rail operations, they are not controlled or directed by the Department for Transport but instead operate as purely private, commercial operations.

The operational side of the industry can be broadly characterised as providing the demand for railway innovation.

Innovation in UK rail

While there is clearly innovation activity in the UK rail industry, designed for and deployed onto the UK railway to varying degrees, the amount of research focused on understanding UK railway innovation activity is relatively limited.

Montero and Finger provide a comparative review of railway regulation, and regulatory reform, and the implications for innovation (with specific reference to opportunities for decarbonisation and digitalisation (Montero and Finger 2020). Gilchrist undertakes a historic analysis of railway engineering research and innovation in the UK railway over the last century (Gilchrist 2009). Divall investigates the networks of technological experts that formed in the UK railway industry in the inter-war period to share knowledge and experience (Divall 2006). Aldcroft investigates the example of the lag in the adoption of new diesel and electric railway traction systems, with the UK railway clinging onto the tried and tested system of steam traction far longer than would have been expected (Aldcroft 1969).

Finally, as referenced above, an initial paper was produced early in this research setting out findings from early investigations into the role of innovation in the UK railway (Burrows et al 2022).

Actors and Institutions

Referencing the discussion earlier in this research concerning the multi-level perspective and innovation systems theory, it is important to further reflect on the actors and institutions who also have a functional role in the UK railway innovation landscape.

The UK Government, devolved administrations in Wales and Scotland, and regional (such as the Mayoral Combined Authorities) and sub-national transport bodes (such as Transport for the North), all play key roles in directing railway services and demand for innovation.

A number of other public bodies all have key functions influencing railway innovation including:

- The Office of Rail and Road (the regulatory body for the railway).

- The Rail Accident Investigations Board (an independent body that investigates accidents and incidents with a focus on driving up safety and preventing future accidents).
- The Railway Safety & Standards Board (an impartial, not for profit organisation owned by the industry to convene and coordinate safety and standards across the sector).
- Transport Focus (an independent transport user watchdog).
- Innovate UK (the Government's national innovation agency, deploying public funding from UK Research & Innovation to support businesses to undertake and commercialise R&D/Innovation).

Figure 2.5 below uses the earlier stakeholder figure (figure 1.6) and groups together these parts of the industry to illustrate the functions of the rail industry in relation to the UK railway innovation landscape.

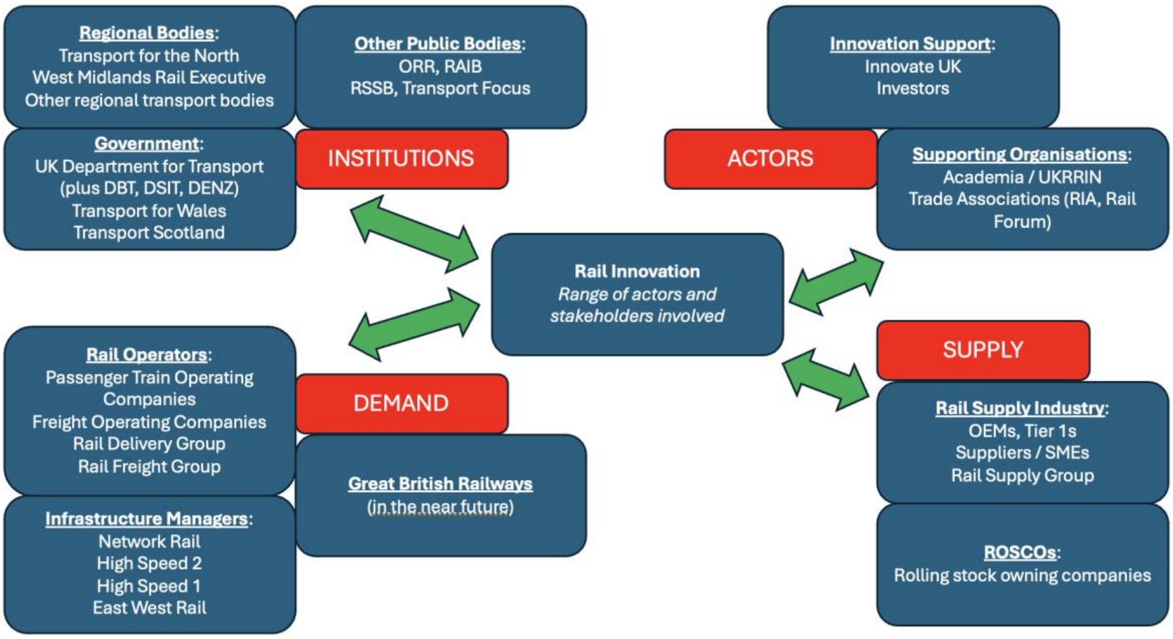

Figure 2.5: diagram illustrating UK railway innovation landscape actors

2.3.2 Learnings from the European experience

Across the Channel, mainland Europe is home to many different national railway networks that have evolved distinctly but jointly comprise a trans-continental transport network.

Unlike road- and air-borne transport that relies on relatively simple and homogenous core infrastructure, the European railway systems have developed using different power and signalling systems along with huge variance in standards and levels of investment.

The European Union (through the European Railway Agency) has been key to providing greater coherence and harmonisation across these systems to enhance the connectivity of people and goods, through the interoperability of these national railway networks. Through several initiatives – such as the introduction of the Technical Standards for Interoperability (TSIs), the European Rail Traffic Management System (ERTMS), the Trans-European Transport Network (TEN-T) – there has been greater cooperation and coordination across European railway systems.

This harmonisation has created the opportunity for the European rail supply industry to serve a more harmonised, simplified, and therefore much larger railway market in economic size. This has provided a much greater market demand for railway innovation suppliers to access, which has been supported by the dedicated European Union research and innovation funding schemes that have been put into place to support European railway systems and their suppliers.

The Shift2Rail programme was introduced in 2014 under Horizon 2020 funding and, as a Joint Undertaking, leveraged industry co-investment to unlock dedicated EU funding, establishing a 7-year budget of EUR 920 million to invest in railway research and innovation across the EU (Shift2Rail 2019). This has been now superseded by the Europe's Rail Joint Undertaking, under Horizon Europe funding, which is projected to spend EUR 1,297 million (Europe's Rail JU 2025). In the establishment of Europe's Rail, the challenges it seeks to address are familiar: changing customer requirements, need for improved performance and capacity, high cost, climate change adaptation and environmental sustainability, legacy systems and obsolescence, interaction with other modes, and increased competitiveness (European Commission 2021).

This scale of investment at the European level to both coordinate the funding and direction of railway innovation on the supply side, through the requirements from the demand side, is aimed at both strengthening the railway supply industry and targeting the improvements needed to boost railway operations across Europe.

Taking learning from the literature review of models of innovation, there is a clear policy objective from the European Union in driving mission-oriented innovation on the railway in the wider context of decarbonising the transport sector to address climate change (European Commission 2018). In addition, the theory of innovation systems can point to the proactive role and coordination of institutions and actors in support of railway innovation activities.

2.4 Innovation in other industries

In section 1.2.5 above, the context of three adjacent transport industries (automotive, aerospace, and shipping) was discussed and summarised. In this section, the respective innovation drivers and systems of those three industries will be investigated in more detail. This analysis will assist in providing contextual and constructive comparison between the UK railway and its closest comparator sectors.

2.4.1 Automotive

The automotive industry (like the railway) is undergoing a profound transformation as it transitions away from combustion engines to electrification. Additionally, the innovative application of digital technologies has been deployed in a variety of ways to continually improve the products being offered to the market. Automotive sector innovation has also widened to the supporting infrastructure required for electric vehicles, and even the business models required that could reshape the sector significantly with the development of autonomous vehicles.

Electrification is the most visible innovation topic for the automotive sector at the present time. With domestic and international regulations requiring the industry to invest in the transition away from fossil fuels (Barroso et al 2022), the sector has a clear incentive to innovate, and with the sector offering a product directly to private buyers in large numbers (unlike the other transport sectors under investigation here) there is a huge volume of sales for manufactures to chase.

The automotive supply industry also has numerous opportunities to deploy innovations as demand for competing battery chemistry technologies, charging infrastructure, and enabling technologies are rapidly deployed at scale in support of electrification (Shahzad & Cheema 2024). In addition, technologies supporting connected and autonomous vehicles also provide innovation opportunities for the sector to develop its product offerings. Alongside these technological developments, come the regulatory developments that are required to keep up with innovation.

As regulations for the deployment of automotive innovations are a domestic concern, the sector faces variations in approach across its global markets with the adoption of these new technologies (Rogge & Goedeking 2024).

Like the other transport sectors, digital technologies offer many opportunities to improve the product offerings from manufacturers and their supply chains. These technologies such as cloud computing, data analytics, internet of things, artificial intelligence, and the roll out of 5G, all provide the basis for new solutions to improve products and services to customers.

Beyond technological innovation the automotive sector's traditional commercial model of private car ownership (unlike the model for rail, aerospace, and shipping) has also provided scope for innovation. Ride hailing and car sharing have both created new transport models, targeting taxi rides and shared car ownership as areas where technology can enable new commercial models for transport services (Acciarini et al 2022).

A further evolution of this commercial model is Mobility as a Service (MaaS) which reverses the traditional model of paying for a transport service (such as a train ticket) and instead offers the purchase of multiple modes of transport to choose from as required for the specific journey (Atkins Transportation 2015). The technological innovation enabling a commercial innovation such as MaaS encourages the automotive industry to explore new revenue streams beyond traditional car sales, as customers can increasingly prioritise access to cars over their full-time ownership.

Finally, innovation has played a vital role in improving automotive manufacturing. The sector has been a leader in improving efficiency, flexibility, and sustainability in its production processes with the adoption of a number of new technologies. These have included:

1. Automation and Robotics – these technologies have been key to improving automotive manufacturing production lines for many years. Artificial intelligence and machine learning have enabled more sophisticated and autonomous systems, while collaborative robots work alongside humans on production lines, improving efficiency and reducing errors (Bogue 2022).
2. Additive Manufacturing - 3D printing technology is being increasingly used for prototyping and producing parts. This allows for rapid iteration in the design process, reducing waste, and efficient use of resources, as well as enabling more complex designs to be produced more simply and quickly (Vasco 2021).
3. Sustainable Manufacturing - the automotive industry has focussed on making production processes more environmentally friendly. The adoption of circular economy principles (emphasising the reuse and recycling of materials) has been adopted into manufacturing processes, along with the use of renewable energy sources, are all key to increasing sustainability in automotive production (Stoycheva et al 2018).

The automotive industry is undergoing a period of rapid innovation, driven by the need for increased sustainability, rapid technological advances, and changing consumer preferences and increased expectations. There are clear parallels between the automotive industry and the railway industry as technological developments offer many opportunities to develop solutions that can deploy digital technologies to improve products and services. Alongside those developments, innovation is being required to support the long-term decarbonisation of the sector as the regulatory environment requires the phasing out of fossil fuels and the electrification of both sectors.

2.4.2 Aerospace

The aerospace industry has seen sustained growth over decades as global demand for air travel has continued to rise. Like the other modes of transport, it is an industry that faces challenges related to its environmental impact and sustainability, as well as needing to deliver continued improvements to operational efficiency, and meeting increasing passenger expectations.

As discussed earlier (in chapter 1.2.5), aerospace faces regulatory oversight from both domestic and international bodies but operates in a highly competitive market where private companies are competing for business in a commercial market driven by private airlines. Alongside that market is a governmental market with huge funding to support the industry and, in parallel, the defence applications and corresponding investment.

Due to the dynamic market where cost and competitive advantage are the crucial drivers, innovation is a key instrument to business success. The acceleration of digital technologies has created many opportunities that the aerospace sector has quickly grasped to support more efficient operations, enhanced safety, and improved experience for passengers. Aerospace has rapidly implemented digital technologies such as data collection and analytics to enable predictive maintenance and improve reliability and maintenance regimes, and digital twin technology is used as standard to improve and accelerate designs before bringing them into operation (Li et al 2022). Meanwhile artificial intelligence is used to optimise route planning and air traffic control, providing improvements to fuel consumption and flight pathing.

Even more than for rail, the aerospace sector is under huge pressure to improve its environmental performance. The sector has set itself sustainability targets in a bid to visibly address the problem of sustainability in its operations. The International Civil Aviation Organisation (ICAO) has established a scheme to offset emissions above 2020 levels to support carbon-neutral growth, and with the overarching aim to halve its carbon dioxide emissions from 2005 levels by 2050 (the CORSIA scheme, ICAO 2024). The International Air Transport Association (IATA) has made a commitment to achieve a net zero level of emissions by 2050 (IATA 2024).

Learning from the review of the literature, we can characterise this as the socio-technical regime responding to pressure from the broader landscape to address concerns around the environmental performance and sustainability of the sector, within the current socio-technical regime. The sector's response to this external pressure from the landscape is manifesting at present in four broad areas:

1. Energy efficiency – as fuel is a direct cost for airlines, there is an ongoing incentive to reduce cost base through improving fuel consumption. Lightweighting of aeroplanes is a key approach (Zhu, Li, Childs 2018), as seen on new plane designs such as the Boeing 787 Dreamliner and the Airbus A350, and more efficient engines (Bravo, Vieira, Ferrer 2022), such as the Rolls Royce Trent XWB, are two key innovation developments actively supporting this agenda.
2. Sustainable Aviation Fuels – fuel made from renewable sources are an area of interest in quickly establishing a transition to more sustainable aviation. Significant industry efforts are seeking to scale up this opportunity to improve sustainability performance (Shahriah & Khanal 2022).
3. Electrification/Hydrogen – another area seeing significant investment is in developing electric, hybrid, and hydrogen planes to rapidly reduce emissions on the route to full decarbonisation of the sector by 2050 (Tom et al 2021), demonstrated by projects such as Wright Electric, Zero Avia, and Airbus ZEROe.

The aerospace industry is investing in rapid innovation across the critical areas of decarbonisation and digital technologies to achieve better services, improved efficiencies, as well as moving towards decarbonisation.

As a highly competitive global industry, operating in a dynamic market subject to market forces, the companies in this sector face continuous pressure to improve and freedom to operate commercially, giving them freedom to choose to make the requisite levels of investment needed to deliver innovation that can ensure they maintain their competitiveness.

2.4.3 Maritime

The international maritime industry is responsible for transporting around 90% of global trade by volume. As with the other modes of transport in this investigation, maritime is undergoing significant transformation with technological developments providing significant commercial incentive to utilise innovation for commercial advantage.

Maritime has traditionally relied on well-established processes – like the railway it has used established technologies to provide motive power, moving from coal to diesel, but with growing pressures from environmental regulations, rising operational costs, and the need for greater efficiency, innovation to support decarbonisation has become essential.

Maritime contributes to approximately 3% of global greenhouse gas (GHG) emissions, making it a key focus area for international regulators. The International Maritime Organisation has set ambitious targets to cut GHG emissions by at least 50% by 2050 compared to 2008 levels, driving demand for significant innovation in the sector (Mallouppas, Yfantis 2021).

For maritime to decarbonise, there are several areas of promise for innovation to be effective:

1. Energy efficiency - one of the most straightforward ways to reduce emissions is by developing energy-efficient ship designs. Modern vessels are being designed with optimized hull forms, improved hydrodynamics, and lightweight materials to reduce drag and fuel consumption (Mallouppas, Yfantis 2021).
2. Operational Efficiency - another way for shipping companies to reduce emissions is by adopting slow steaming practices, where ships operate at reduced speeds to cut fuel consumption. While this increases journey times, the fuel savings and reduced emissions often outweigh the delays. Furthermore, the development of new technologies enables innovations including better logistics management and just-in-time arrival systems to be deployed, which ensure ships arrive at ports when berths are available, which helps to reduce idle time and unnecessary fuel consumption (Degiuli et al 2021).
3. Sustainable Power Systems – as with rail, removing fossil fuels from the energy mix is a key factor. Traditional heavy fuel oil that is used by shipping is highly polluting, and the IMO’s 2020 global sulphur cap (Zisi, Psaraftis, Zis 2021) has provided an incentive to push the industry towards cleaner fuels, such as Liquified Natural Gas, ammonia, hydrogen, and biofuels, although this will still require significant policy and market

intervention from actors and institutions to drive the industry towards adopting such technologies against a backdrop of a competitive and growing market (Gossling, Meyer-Habighorst, Humpe 2021).

As a highly competitive globalised market, private maritime companies face the same two governing pressures that the UK railway faces – providing improved services while managing lower operating costs. Unlike the UK railway, those pressures come from market forces rather than the Government control as the ultimate bill-payer through subsidies.

Maritime companies have identified a raft of opportunities with the rapid advancement of digital technologies that can significantly improve their operations, in terms of both operating costs and performance (Tijan et al 2021). There are several examples to illustrate this such as the use of blockchain technology for cargo tracking and transparency, artificial intelligence to optimise shipping operations and route-planning, application of sensing technologies to provide real-time monitoring of ship performance and also of cargo condition, automated ports that can enhance operations, and autonomous ships that can reduce costs and improve performance (Marine Link 2025, Raza et al 2023).

2.4.4 Summary of Railway and Adjacent Industries

The UK railway innovation landscape is heavily influenced by the Government due to its significant influence on the commercial demand side, as it exerts management control over passenger railway operations at a structural level. This is considerably greater than in the three adjacent industries.

Using the example of climate change and the push for transport decarbonisation, the role of policy and regulation, and therefore the role of institutions and actors, is a key influence in incentivising and motivating innovation activity on the supply side in all four industries.

Building on the literature review, the theoretical models of innovation investigated all provide relevant learning to support analysis of the UK railway innovation landscape and the investigation of how to describe it and to build a model of how it is, and a conceptual framework of how it could be.

2.5 Chapter Summary

In this chapter, a review of the relevant literature and comparative analysis has established that a model of innovation to enable a better understanding of the UK railway can build from three key learnings:

(1) The importance of considering innovation supply and demand perspectives within a broader view of the innovation system of actors and institutions who have a role or influence in the innovation landscape – building on Rothwell's five generations of innovation process models, Chesbrough's theory of open innovation, and the theories of innovation systems.

(2) Innovation as a cyclical rather than linear process with three layers – the landscape, the socio-technical regime, and the niches, which group together the actors and influences in the innovation landscape – and three phases of the innovation cycle, seen within the context of a socio-technical regime – the present landscape or state of the art, the development of both the technology (supply side) and the context (demand side), and the outcome delivery as a result of the technological transition. The multi-level perspective is a valuable framework in drawing out and understanding layers, or areas of activity and influence, when it comes to identifying the broad areas of influence within the innovation landscape.

(3) Combining much of this learning, the research summarises the learning of this chapter into three fundamental and concurrent parts and roles to the innovation process cycle, described as:

    a. Technical – a supply side perspective, considering what can be done and by whom.
    b. Contextual – a demand side perspective, considering problems that need addressing, and what can be accepted.
    c. Institutional – a blended perspective, considering the interactions between all relevant actors and with a broader perspective of the overarching landscape. The Neo-Schumpeterian/Innovation Systems and Social Constructivist models of innovation theory are influential in this research. No

understanding of the UK railway innovation landscape can ignore the roles of actors and institutions – beyond the innovation suppliers and buyers – in heavily influencing this landscape.

These key learnings are summarised in figure 2.6, providing an initial consideration to inform the understanding of the research investigation into describing the UK railway innovation landscape.

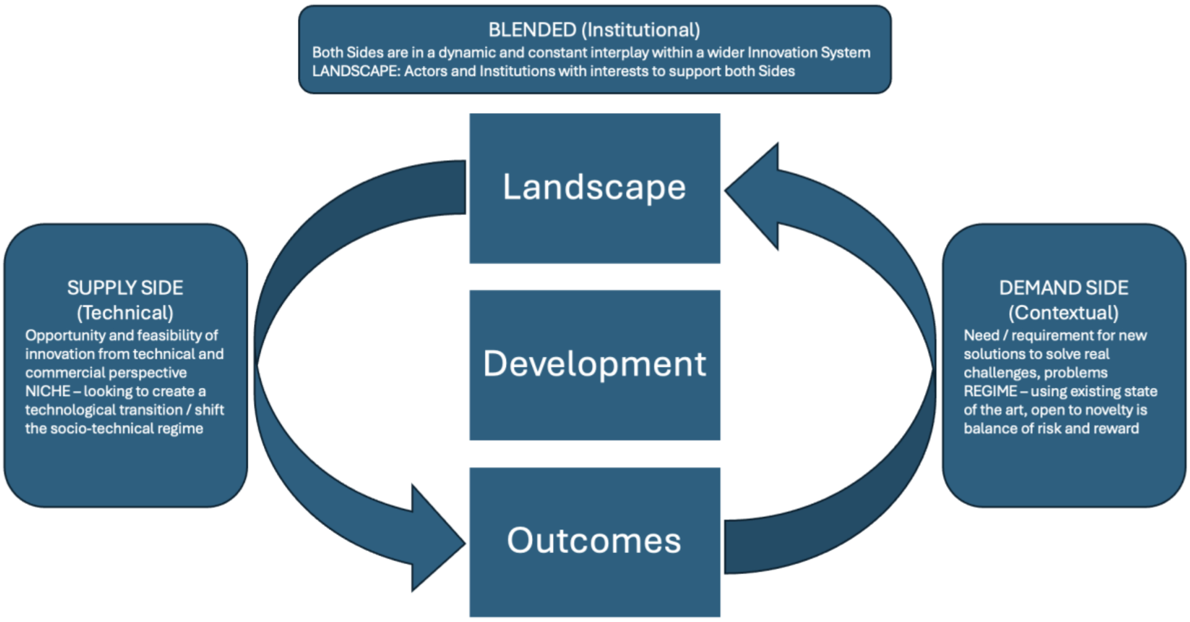

Figure 2.6: Summary of key theoretical learnings from literature review

Additionally, the review has demonstrated a clear gap in the literature addressing theoretical understandings of innovation and their practical applications to the railway.

In the next chapter, the research moves to framing the thesis, identifying the primary data that needs to be collected and reviewing the appropriate methodology to collect it.

Chapter 3: Methodology

Chapter Structure

3.1 Introduction

In this chapter, the problem that this research seeks to address is framed, alongside how the application of the systems approach, and the design of the Research Questions, can enable the research to answer this problem. The methodological design for undertaking the research project is set out and the methodology for how the data will be analysed to answer the Research Questions is also established.

3.2 Framing the problem/thesis

The railway is a complex system (see chapter 1.2.3 above) and a critical part of the national transport network infrastructure; with multiple actors; with a significant role for governments, regulators, and public bodies; with huge capital investment requirements and long timescales; and with high health and safety requirements due to the safety-critical nature of operations.

These factors combined demonstrate why the railway is a highly regulated industry which makes it less easy to apply innovation models directly onto, because it is not a purely commercial sector. Instead, the railway provides a critical public good requiring significant public investment to deliver the objectives sought after, but with requirements to generate efficiency in operational costs, as well as increasing usage, reliability, and overall operating performance.

Referring to the research questions, this research will create a model of the UK railway innovation system that can be used to build a conceptual framework that can support and enable more innovation to succeed on the UK railway.

- **RQ1: How is innovation currently supported and enabled, or not, to be introduced onto the UK railway?**
- **RQ2: What are the critical factors that act as either enablers or blockers to innovation successfully being introduced onto the UK railway?**
- **RQ3: Who are the key actors involved in UK railway innovation?**

- **RQ4: Can we create a model of the UK railway innovation system (recognising that it is a complex system) to understand the factors that drive the success or failure of innovation on the UK railway?**
- **RQ5: Can we develop a conceptual framework, utilising this model, that can enable the more successful introduction of innovation onto the UK railway?**

To do this, a research methodology is required to provide a logical structure and sequence. In chapter 1.5, the research approach was established using a modified version of the V-model for systems engineering - this is set out again in figure 3.1 with the relevant section highlighted for this chapter of the research.

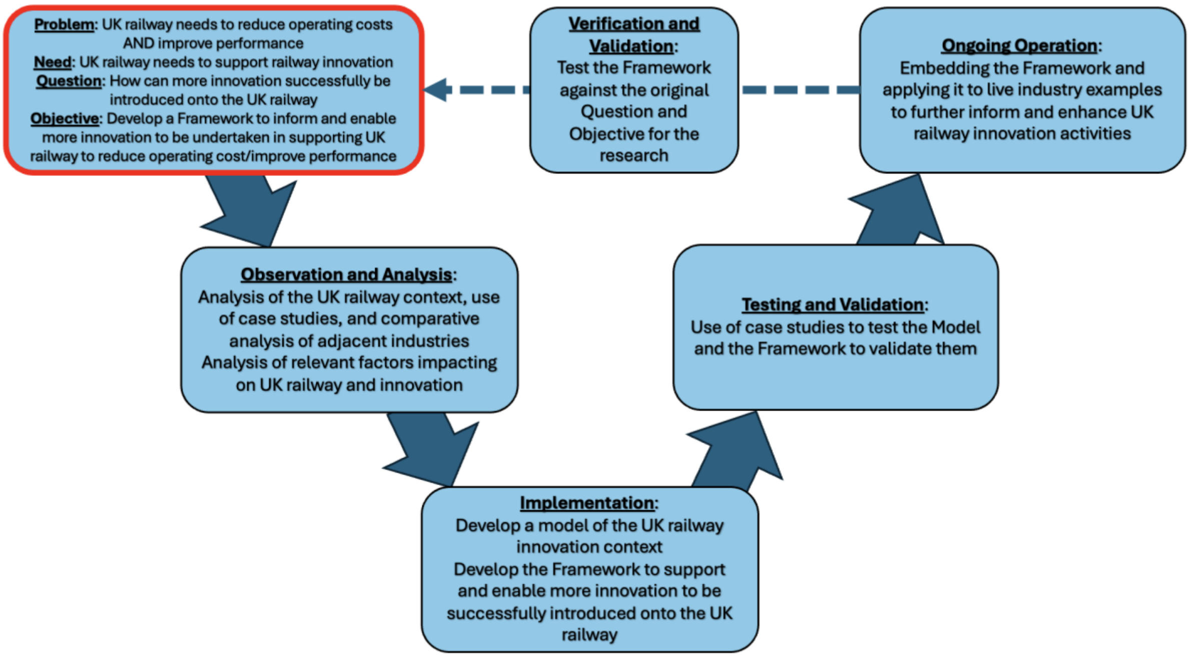

Figure 3.1: Systems approach to this research (with relevant section for Chapter 3 highlighted)

In this Chapter, the methodology is established for collecting the relevant data required to undertake the analysis. This is a key step in moving from the establishment of the problem through to the analysis phase of the investigation.

The investigation will build on the previous chapters to establish these factors:

Need: How do you enable the introduction of innovation onto the UK railway? Where does the demand for innovation come from and how can it be enabled and incentivised?

Problem: We understand the clear requirement for rail to make use of innovation to reduce costs and improve performance, but there is a lack of innovation and a lack of impact from innovation. Therefore, the government and industry repeatedly call for more innovation to support the UK railway to deliver better services, more cost-effectively.

Question: How do we enable and support more successful innovations to be introduced onto the UK railway? What are the barriers to introducing innovation onto the UK railway and how can we mitigate them?

Objective: To develop a Framework that can enable the successful introduction of innovation onto the railway more quickly and effectively.

Taken together the need and the problem provide the thesis, which is the focus for the research (the question) and the objective (the desired outcome of the research).

The models of innovation, from the literature discussed in Chapter 2, along with the contextual research on the UK railway and the comparative research of other industries and other railway systems, give a clear insight into the how and why for innovation, but they do not give a clear answer in the context of the UK railway innovation landscape. This frames the question and objective for this research investigation.

The main part of the research investigation is the collection of the required data to support the observation and analysis in the following chapter. The remainder of this chapter sets out the methodology for collecting the relevant data, followed by how the analysis of this data will be undertaken and the approach used to build the model and develop the framework.

3.3 Research Design

The research will use several methods for collecting the required data. Building on the models of innovation discussed in chapter 2, the research will look to establish sufficient qualitative and quantitative data, alongside the comparative analysis of the UK railway and other industries and countries, to support a rigorous analysis. The methodology to inform that analysis commences with a detailed PESTLE (Political, Economic, Social, Technological, Legal, and Environmental external factors) analysis to observe and analyse the UK railway market and the landscape for innovation. In particular, and based on learning from the previous chapter, this analysis focuses on:

- the supply of, and demand for, innovation onto the UK railway.
- the phases of Landscape, Development, and Outcomes as key components in the innovation cycle.
- the critical concurrent roles and considerations of technical, commercial, and actors, in the innovation cycle.

The PESTLE analysis will demonstrate the Need *(How do you enable the introduction of innovation onto the UK railway? Where does the demand for innovation come from and how can it be enabled and incentivised?)* and the Problem *(We understand the clear requirement for rail to make use of innovation to reduce costs and improve performance, but there is a lack of innovation and a lack of impact from innovation. Therefore, the government and industry repeatedly call for more innovation to support the UK railway to deliver better services, more cost-effectively)* and will provide the evidence of their shape, influence, and impact.

Building on that PESTLE analysis, the investigation will bring in significant additional quantitative and qualitative data by respectively undertaking (1) an online survey (to establish a significant relevant quantitative dataset), and (2) interviews with key actors (to provide targeted qualitative evidence, building on the quantitative dataset).

Finally, an analysis of railway innovation case studies will be undertaken – looking at both UK examples, and examples from comparable overseas railway systems.

This methodology allows for a broad base of evidence to be collected and analysed to support the investigation.

This research makes use of multiple, mixed methods as tools for constructing a detailed understanding of the reality of the landscape being research – the UK railway innovation landscape. Methods have been rightly described as tools for researchers to utilise (Hesse-Biber 2010). This research will make use of several tools to provide a combination of sources of knowledge – both deep and broad, subjective and objective – to construct an understanding of the UK railway innovation landscape to then inform the objective of the research (a Framework that can enable the successful introduction of innovation onto the railway more quickly and effectively).

3.3.1 PESTLE Analysis

A PESTLE analysis is a means of identifying and assessing relevant external factors that can influence the decision-making of any organisation. The acronym lists a set of six external influencing factors – Political, Economic, Sociological, Technological, Legal, and Environmental – these factors are explained in table 3.1 with reference to this research specifically.

Political	External factors driven by the government, public policy, political factors, and political actors
Economic	External factors driven by the economy
Sociological	External factors driven by societal issues and influences
Technological	External factors driven by technological influence and developments
Legal	External factors driven by the law and the legal system
Environmental	External factors driven by the environment, environmental issues and concerns

Table 3.1 External factors identified and analysed using a PESTLE Analysis

Using a PESTLE analysis provides a strategic framework to analyse and comprehend these six external influencing factors, allowing us to assess and understand the relative impacts of these factors on the study subject (Christodoulou, Cullinane 2019). This research will utilise a PESTLE analysis to identify and understand the external factors that influence innovation activity on the UK railway, and whether and how they act as enablers or barriers.

3.3.2 Quantitative Research Methods

Quantitative research methods measure a studied phenomenon by gathering and analysing data to better understand the phenomenon (Watson 2015).

Quantitative research methods are a valuable tool and a fundamental part of modern science (Holton, Burnett (ch.3), in Swanson, Holton (eds), 2005). Using quantitative methods aims to provide objectivity, and to provide a generalised set of findings that are free from any preconceived ideas or bias on the part of the researcher (Harwell (ch.10) in Conrad, Serlin (eds) 2011). Quantitative methods of research can provide the generalisation of findings but potentially with a lower degree of certainty (depending on the complexity of the research procedures put in place), meaning that conclusions can be more easily drawn from the findings (Holton & Burnett, in Swanson, Holton (eds), 2005). Quantitative research can use findings to draw a more generalised set of inferences about characteristics in a wider context (Harwell, in Conrad, Serlin (eds) 2011).

A survey can provide a wealth of valuable quantitative data that can be used to describe a context in a generalised manner. However, it is in the nature of quantitative data collection to provide parameters around the potential responses through the design of the questions used to collect the quantitative data (Creswell, Creswell (ch.18), in Swanson, Holton (eds), 2005). Quantitative data is collected at scale to provide a description of a landscape or events through controlled observation.

For this research, quantitative data will be important to provide an objective view of the UK railway innovation landscape. The quantitative data was collected using an online survey designed using non-experimental methods with the objective of obtaining a detailed and objective description of a real-world phenomena - the landscape for UK railway innovation - as completely and accurately as possible (Tolmie, Muijs, McAteer 2011).

The online survey used a correlational design to collect responses from professionals with experience of the railway industry, predominantly but not exclusively in the UK, to get a broad set of perspectives and understanding of the UK railway innovation landscape.

3.3.3 Qualitative Research Methods

In contrast with quantitative research methods, qualitative research methods are focused on obtaining subjective, rather than objective, information on a subject by understanding the experiences and perspectives of participants (Harwell (ch.10) in Conrad, Serlin (eds) 2011). Gerring (2017) contrasts qualitative data as being noncomparable due to it being a unique observation or inference, in comparison to quantitative data which is defined to make it comparable across a larger dataset.

Key to this methodological approach is the perspective that participants are being interviewed as experts and that reality is socially constructed, therefore there is intrinsic value in understanding the unique realities of experts to achieve a better understanding and explanation of the reality being investigated (Hesse-Biber 2010).

Interviews are the most effective ways of obtaining detailed information and insights into an expert's domain (Taherdoost 2022). This research used 43 expert interviews to collective qualitative data. The interviews were semi-structured using a core of pre-determined questions to provide a consistent guide and coherent flow to the interviews, but with supplementary and clarification questions used as appropriate to probe particular topic areas (Taherdoost 2022). The interviews were conducted in person and one-to-one to enable a candid discussion, thereby requiring a confidentiality statement to ensure that views were expressed completely openly and honestly; this ensured that the research obtained an accurate assessment of each interviewee's perceptions and reflections on the UK railway innovation landscape.

Qualitative data collection was deemed essential to this research to be able to access the greater in-depth knowledge of certain participants (Bachiochi and Weiner (ch.8) in Rogelberg (ed.) 2004) to provide a richer understanding of the UK railway innovation landscape.

In preparing interviews to obtain qualitative data, it has been important to undertake an analysis of relevant actors and stakeholders to obtain a representative and robust sample to support the research (Franco-Trigo et al 2020). Three core actor and stakeholder categories were identified to establish a minimum sample covering all relevant areas from across the UK railway innovation landscape – these are set out in table 3.2.

Group 'SI' Supply Industry / Innovation Supply	Group 'OP' Rail Operations / Innovation Demand	Group 'ST' Stakeholders, Others
Rail supply industry actors including OEMs, Tier 1 contractors, SMEs, consultancies, ROSCOs, and the Department for Business and Trade (DBT)	Railway operating industry including Train Operating Companies, Freight Operating Companies, Network Rail, and the Department for Transport (DfT)	Trade associations, the railway sector trade press, international actors and organisations, and regulatory and advisory bodies

Table 3.2 Actor categorisation for qualitative data collection

3.3.4 Mixed Methods

Mixed methods research deploys both quantitative and qualitative research methods together to inform the design of the research and use analysis from both types of data to address the research question (Tashakkori & Teddlie 2003). The purpose of mixed methods research is to address areas that neither of quantitative nor qualitative alone can fully capture and explain the breadth of issues in certain research problems (Ivankova, Creswell, Stick 2006). More positively, using both quantitative and qualitative methods to support research can be effective in strengthening research findings (Creswell, Creswell (ch.18), in Swanson, Holton (eds), 2005; Bachiochi and Weiner (ch.8) in Rogelberg (ed.) 2004).

Mixed methods research allows researchers to use any number of different methods and approaches to collect, analyse, and interpret data thereby removing constraints to research approaches (ie quantitative or qualitative) and providing an open approach for researchers to conduct their studies (Harwell (ch.10) in Conrad, Serlin (eds.) 2011).

This research uses mixed methods, collecting both quantitative (from an online stakeholder survey) and qualitative data (from interviews with experts). The research utilises the approach of data triangulation through the collection of data from multiple sources (Bachiochi and Weiner (ch.8) in Rogelberg (ed.) 2004) to investigate the research questions.

In collecting and analysing the data, consideration has been given to issues regarding research design (Ivankova et al 2006). These include the relative weight given to the quantitative and qualitative data gathered, and when to collect and analyse the respective datasets (Ivankova et al 2006, Hesse-Biber 2010), and also consideration as to the author's own perspectives and reality from previous experience and knowledge gained in the field (Hesse-Biber 2010). To address these issues, the data has been integrated to provide a multilayered investigation (Hesse-Biber 2010) and a critical approach has been developed.

3.3.5 Critical theory and research methodology

Analysing and interpreting both the qualitative and quantitative data using mixed methods will still require a theoretical standpoint to build from.

This research draws on experience from the critical legal studies movement and the development of critical theory. The critical legal studies movement rejected formalism (that there is a method of justifying all facts about life and society to enable a complete, coherent set of rules that can be deduced) and objectivism (that there is a natural legal and moral order to all life that exists separately and abstractly) (Unger 1983). Instead, critical legal studies highlighted the 'radical indeterminacy' of law (Unger 2015) - that there was no formal self-justifying system of laws with an objective truth underpinning them, instead laws were open to interpretation and therefore to the perspectives and preferences of the interpreter.

Critical legal studies built on critical theory, a philosophical and multidisciplinary approach to social sciences and humanities that seeks to challenge society by analysing and better understanding it to change it for the better (Morrow 1994; How 2003).

In using critical theory to inform the research design and methodology, the research seeks to establish a body of empirical evidence (using mixed methods of data collection and then integrating them to undertake an analysis); from here the research moves into normative theory to develop a conceptual framework to understand the UK railway innovation landscape and how it ought to be in order to address the core objective set by the research - *to develop a Framework that can enable the successful introduction of innovation onto the railway more quickly and effectively*.

The normative theory is important as the landscape for UK railway innovation is constructed and shaped by the actors involved. This builds on the social construction theory discussed above. The empirical evidence is important to inform the research, but it requires a critical approach to its analysis to fully inform an effective framework for railway innovation.

This aligns with the constructivist perspective of systems engineering, referred to in chapter 1.5, as the selected systems approach being used for this research. The constructivist approach – as per the critical approach – considers that a system is not 'presented' to the observer as an objective truth but is instead 'recognised' subjectively by the observer as being a system (INCOSE 2025).

As a consequence, this research deploys mixed methods and can be described as using a concurrent transformative design and is illustrated in figure 3.2 (based on Creswell et al 2003). The concurrent transformative design approach can be characterised as the approach where the collection and analysis of both quantitative and qualitative data is undertaken concurrently (Almeida 2016). The transformative approach to mixed methods research focuses on taking a critical approach where there is an advocacy role for the outputs of the research to, ultimately, create a better world (Sweetman et al 2010).

Figure 3.2: Mixed methods research using concurrent transformative design approach

3.3.6 Analysis of railway innovation case studies

To further inform the empirical evidence base and support the data analysis, the research uses several railway innovation case studies to investigate and analyse the evidence and to inform the development of the conceptual framework.

The case studies all focus on the field of sustainable railway traction power systems specifically to have a clear and comparable topic within railway innovation as the subject matter.

The topic of alternative railway traction power systems is of significant interest globally, and the focus of a significant amount of railway innovation activities. Given the railway is a relatively sustainable form of transport, and in an era where climate change is a dominant subject, this field provides ample opportunity to collect relevant and recent evidence to inform the research.

Several case studies from the UK railway innovation landscape will be used, with a small number of international examples in addition to provide comparative data and analysis.

3.3.7 Model of UK railway innovation landscape and Conceptual Framework

The research methodology outlined above will be synthesised to provide an integrated body of empirical evidence setting out how UK railway innovation landscape appears to be. This will use the quantitative and qualitative data collected and analysed to provide a model of how the UK railway innovation landscape currently operates. This model will use the empirical data collected and analysis from it to construct an observed, descriptive assessment of what the UK railway innovation landscape appears to be at the present time. The model will be tested to inform the research as to where the enablers and barriers presently exist, and who the key actors and stakeholders are in the UK railway and their importance and influence on the success or failure of innovation.

The model will provide the basis for the construction of a conceptual framework of the UK railway innovation landscape which can be tested to identify how it ought to be to successfully deliver more innovation. The research will use the framework to provide a normative theoretical assessment of how the enablers of innovation can be enhanced and the barriers to innovation can be mitigated to address the problem the research seeks to address (*to develop a Framework that can enable the successful introduction of innovation onto the railway more quickly and effectively)*.

The research will use the critical theory approach to identify and explore how the UK railway innovation landscape can be improved upon in order to enable more innovation to succeed and provide an answer to the research problem (*we understand the clear requirement for rail to make use of innovation to reduce costs and improve performance, but there is a lack of innovation and a lack of impact from innovation. Therefore, the government and industry repeatedly call for more innovation to support the UK railway to deliver better services, more cost-effectively)*.

3.3.8 How the Methodology addresses the Research Questions

The methodology for this research has been informed by the Research Background in chapter 1 and the Literature Review in chapter 2.

The five Research Questions (chapter 1.4) - that have been designed to frame the research - are the focal point for establishing the design of the Methodology for this research.

- **RQ1: How is innovation currently supported and enabled, or not, to be introduced onto the UK railway?**

The first question sets out the requirement for empirical research to understand and describe the UK railway innovation landscape. To develop a full understanding, a mixed methods research approach has been selected, combining quantitative and qualitative data collection from UK railway innovation landscape actors, to obtain as full a descriptive understanding as possible.

- **RQ2: What are the critical factors that act as either enablers or blockers to innovation successfully being introduced onto the UK railway?**

From the empirical understanding of the UK railway innovation landscape, analysis of the data collected will inform the research. This analysis integrates the primary data from the quantitative and qualitative research and is combined with further research looking at railway innovation case studies to develop and test the analysis.

- **RQ3: Who are the key actors involved in UK railway innovation?**

Building on the analysis to support Research Question 2 above, an analysis of the actors and stakeholders involved in the UK railway innovation landscape will also be undertaken. This will be used to both inform the identification of key actors for interviews, and to build the model of the UK railway innovation landscape as a system (see below).

- **RQ4: Can we create a model of the UK railway innovation system (recognising that it is a complex system) to understand the factors that drive the success or failure of innovation on the UK railway?**

The analysis from the previous Research Questions is then utilised to construct an empirical model of the UK railway innovation landscape. The model is used to test and validate the empirical analysis, and to construct a conceptual framework that can build from this baseline model.

- **RQ5: Can we develop a conceptual framework, utilising this model, that can enable the more successful introduction of innovation onto the UK railway?**

Finally, the research will use the model of the UK railway innovation landscape to construct a normative theoretical framework of how the UK railway innovation landscape ought to be. This framework can then answer the central research objective of identifying how to enable more innovation to be successfully developed and implemented onto the UK railway.

3.4 Chapter Summary

In the first three chapters, the problem has been defined along with the thesis that is the subject of this investigation. The research objectives have been identified and the research questions defined. The research approach to be taken has been set out and the research methods have been designed and explained. These are all set out in table 3.3.

The Research Problem (Thesis)	There is a very real need for the UK railway – how do you help more innovation to be successfully introduced onto the railway? Demand for innovation is established – the current context is very difficult for the UK railway (reduce costs and improve performance). How do we help supply side to succeed, how do we stimulate and support demand side to buy it?
Research objectives / scope	To develop a Framework to enable the successful introduction of innovation onto the railway more quickly and effectively.
Research questions	▪ RQ1: How is innovation currently supported and enabled, or not, to be introduced onto the UK railway? ▪ RQ2: What are the critical factors that act as either enablers or blockers to innovation successfully being introduced onto the UK railway? ▪ RQ3: Who are the key actors involved in UK railway innovation? ▪ RQ4: Can we create a model of the UK railway innovation system (recognising that it is a complex system) to understand the factors that drive the success or failure of innovation on the UK railway? ▪ RQ5: Can we develop a conceptual framework, utilising this model, that can enable the more successful introduction of innovation onto the UK railway?
Research approach	Systems approach
Research methods	Mixed methods, combining: ▪ PESTLE analysis

	▪ Quantitative data ▪ Qualitative data ▪ Case studies ▪ Comparative analysis ▪ Critical approach and analysis

Table 3.3 Summary of research problem, questions, approach and methods

The logical structure of this research investigation is summarised in figure 3.3.

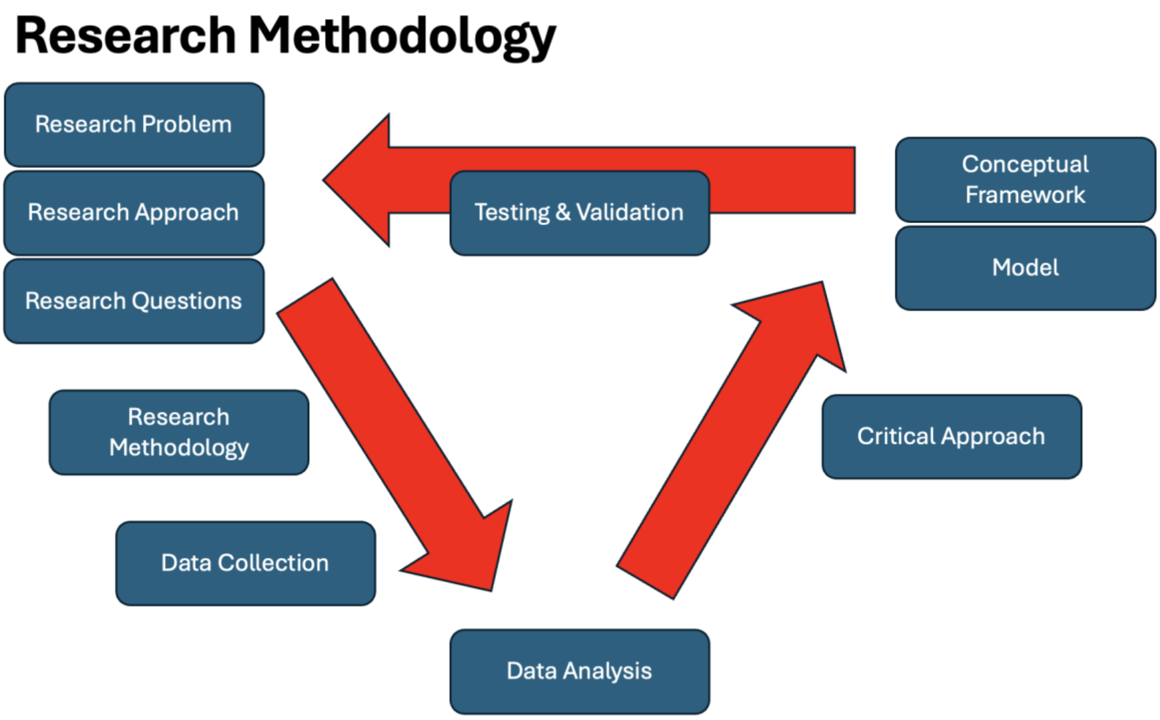

Figure 3.3: Summary of the research methodology

The remaining chapters are structured to follow this methodological approach:

<u>Chapters 4-8 – Observation and Analysis</u>

In the next chapters, the data collection and analysis is explained applying the methodology set out above in this chapter. Using the analysis undertaken, a model of the UK railway innovation landscape will be established to describe the present situation.

<u>Chapter 9 – Introducing the Framework</u>

The outputs from these chapters allow for the construction of the conceptual framework for enabling the introduction of innovation onto the UK railway. This framework will present a system of how the UK railway innovation landscape ought to be in order to better enable innovation to be successfully implemented onto the UK railway.

Chapter 10 – Testing the Framework

The framework will be tested using the topic of alternative railway traction power systems as a worked example case study. Reference will be made to the actual innovation case studies assessed in chapter 7, to provide a comparative example of descriptive versus normative assessments of these case studies (how they are vs how they ought to have been).

Chapter 11 – Verification and Conclusions

In the final chapter, the research will verify the Framework and validate its outputs against the original research question and objective. The research will conclude with suggestions on how the framework could be embedded to enable practical benefits and improvements, as well as suggest further research building on this work.

Chapter 4: Observation and Analysis (External and Internal Factors)

Chapter Structure

4.1 Introduction

4.2 PESTLE Analysis of Factors External to the Railway Industry

- 4.2.1 Political: External factors driven by the government, public policy, political factors, and political actors
- 4.2.2 Economic: External factors driven by the economy
- 4.2.3 Social: External factors driven by societal issues and influences
- 4.2.4 Technological: External factors driven by technological influence and developments
- 4.2.5 Legal: External factors driven by the law and the legal system
- 4.2.6 Environmental: External factors driven by the environment, environmental issues and concerns

4.3 Analysis of Factors Internal to the Railway Industry

4.4 Chapter Summary

In this chapter, the research undertakes the observation and analysis phase within the research approach set out in the systems model, demonstrated in figure 4.1.

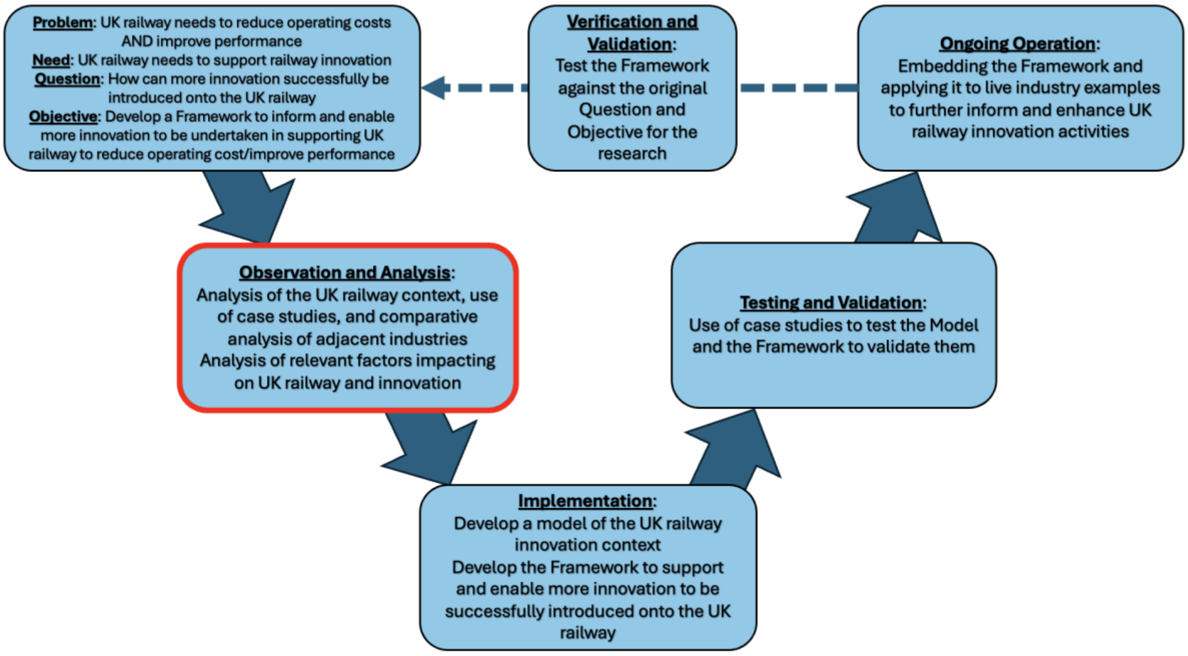

Figure 4.1: Systems approach to this research (with relevant section for Chapter 4 highlighted)

4.1 **Introduction**

The observation and data collection are split into 4 chapters:

In this chapter, a detailed PESTLE analysis has been undertaken to identify the external factors influencing and impacting on how innovation can or could happen in the UK railway. In addition, an analysis of the internal factors that influence and impact on the UK railway innovation landscape has been undertaken to provide a full survey of potential impacting factors.

Secondly, in the next chapter, an online survey has been designed and undertaken to collect quantitative data to provide a broader sample to support the PESTLE analysis and to inform the qualitative data from the interviews. The quantitative data has been analysed to produce a broad understanding and assessment of the UK railway innovation landscape. This has been used to inform the qualitative data collection and analysis.

Thirdly, in chapter 6, a series of detailed, qualitative interviews have been undertaken with a representative range of key actors in the field who provide a balanced and broad view across the UK railway innovation landscape. These interviews have also informed, tested, and enhanced the PESTLE analysis and the survey findings.

Fourthly, in chapter 7, building on those findings, the investigation has assessed a number of recent railway innovation projects in the UK to test and validate the findings, along with examples from other European railway systems to provide further comparative analysis and understanding. These case studies are all focused on the field of alternative railway traction power systems to enable a clear and relevant comparative analysis.

The observation and data collection will be used to inform the analysis of the UK railway innovation landscape.

4.2 PESTLE Analysis

The UK railway innovation landscape is complex with many key actors, institutions, and stakeholders across a range of areas. The PESTLE analysis is an effective method for identifying the range of external factors that can have an impact on the research subject (Christodoulou, Cullinane 2019). Such an analysis identifies potential external factors across six areas: Political, Economic, Social, Technological, Legal, and Environmental. A PESTLE analysis has been used to provide an effective methodology for identifying the range of external factors influencing and impacting the UK railway innovation landscape.

The United Kingdom's railway industry is a critical component of its national infrastructure, supporting economic growth, social mobility, and environmental sustainability. As the UK transitions toward a greener and more efficient transport system, the demand for railway innovation exists (see chapter 1). The aim of this PESTLE analysis is to provide a rich contextualisation of the UK railway innovation landscape to inform the quantitative and qualitative data collection and analysis, and to underpin the critical approach of this research.

The PESTLE analysis has been undertaken using the primary and secondary sources referred to in Chapters 1 and 2, combined with an analysis built from the practical experience of the author. However, that experience has sought to be as objective as practicable. A number of Government and industry documents have been used to inform this PESTLE analysis, providing a broad and rich overview to draw out the key themes clearly.

The PESTLE analysis is informed by the literature review in chapter 2 (see above), in particular the theoretical analysis of models of innovation, including theories of open innovation, mission innovation, neo-Schumpeterian theories of innovation systems, and constructivist theory of innovation.

Figure 2.6 is reproduced again below for reference; in it the theoretical learnings are set out:

- The importance of considering the innovation supply side and the innovation demand side and their respective roles in driving the innovation process. In Rothwell's five generations of innovation process, and Chesbrough's model of open innovation, the respective roles and their influence is important to consider along with the purpose of innovation. In addition, mission-driven innovation provides an understanding of using policy instruments to deliver strategic objectives, especially the difficult, macro-problems such as climate change that need a large, coordinated response to address them.
- The environment for innovation, which includes the landscape for innovation (the broad context), the socio-technical regime (the UK railway industry), and the niches (the small spaces for radical innovations), and the roles of, and interactions between, these three layers. The multi-level perspective theory provides a valuable contextual underpinning of how these layers interact and can influence the UK railway innovation landscape.
- The importance of considering the roles and influence of actors and institutions beyond the direct innovation supply and demand areas (the transactional parties who will be selling or buying innovations). The neo-Schumpeterian theory of innovation systems, and the social constructivist theory of innovation both provide theoretical insights into the roles of actors and institutions. They can incentivise and motivate innovation processes as well as the acceptance and diffusion of technological advances.

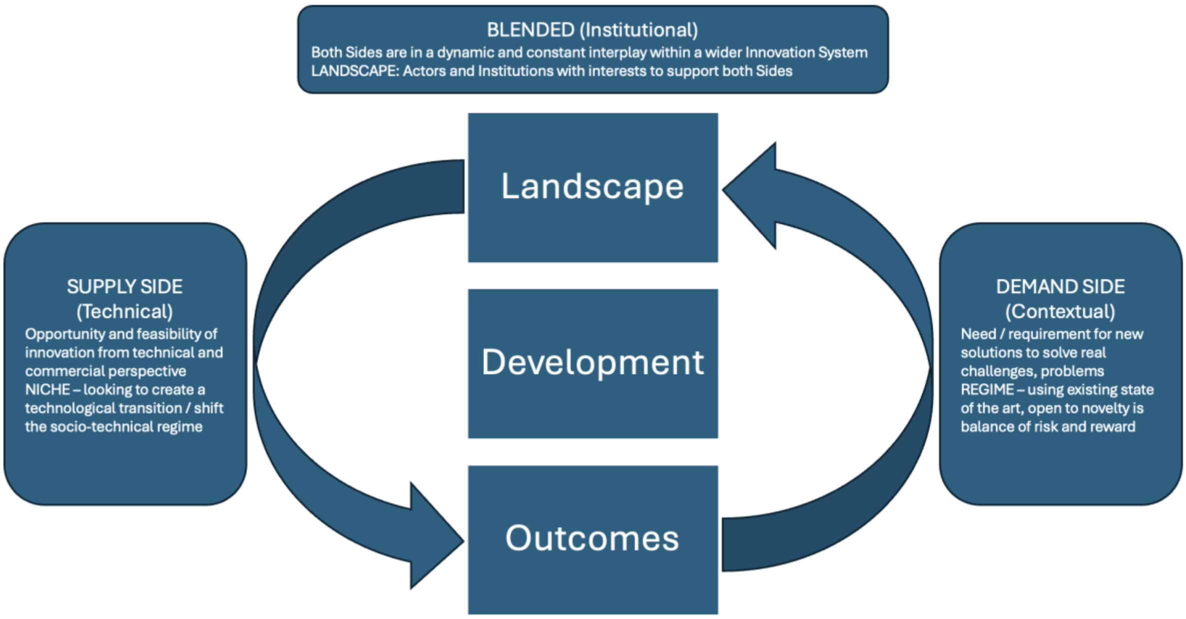

Figure 2.6: Summary of key theoretical learnings from literature review

The PESTLE analysis works through the set of six external factors with an assessment of how these factors impact the UK railway innovation landscape.

4.2.1 Political: External factors driven by the government, public policy, political factors, and political actors

The UK government plays a critical role in enabling and incentivising innovation in the railway sector through funding, regulations, policy, and (ultimately) procurement. Political factors play a major role in influencing the railway industry and fundamentally shape the UK railway innovation landscape on both the supply side and the demand side.

(1) Railway as a Public Good

The railway network is critical national transport infrastructure asset of significant scale and importance. It plays a major enabling role in supporting a number of public policy objectives across economic, social, and environmental themes.

As publicly owned infrastructure, there is a political imperative to ensure that the railway infrastructure is well looked after and well-used to derive maximum benefit and value to the country. To this end, there is significant political influence and interest in seeing innovation being used to maintain the railway as a public good, making it attractive to customers and providing a wide variety of economic, social, and environmental benefits. This is a clear demand side driver for innovation and a firm role for political actors in enabling railway innovation.

(2) Public Investment Requirements for Railway

Railways require significant capital investment – both for regular operations and maintenance, and for investment projects in upgrades and new infrastructure. Political objectives decide how available public funds are prioritised for the railway against other public spending requirements.

In the five years from 2019 to 2024, the UK Government allocated £67.4bn to Network Rail to spend in Control Period 6 on operations and maintenance, as wells as renewals and enhancements (ORR 2024). Of that £67.4bn pot of money allocated by the UK Government to Network Rail, £245m of that was allocated to research, development, and innovation spending (RIA 2024).

However, Network Rail, as the UK railway infrastructure manager, are not just a direct investor in research, development, and innovation. Their market spending power can significantly influence and shape the UK railway innovation landscape, or act as a major barrier, depending on their requirements and investment priorities.

Major projects such as High Speed 2 and Crossrail generate significant demand for innovation, with committed long-term funding available to procure innovative products and services. Additionally, ongoing major upgrades such as railway infrastructure electrification can generate a pipeline of demand for innovation.

(3) Political Interests and Priorities

As mentioned above, political interests and priorities will shape where and how public funds are allocated, to support public policy objectives. These decisions will be steered by several considerations including the point in the electoral cycle and public opinion; ultimately, railway is one of many policy areas competing for finite public funding.

Political issues such as the renationalisation of the railway, the appetite for private sector investment, opinion on relative value for money, and alignment with strategic objectives such as Net Zero targets, are all factors influencing what funding is available and how it is spent. Again, the important role of political actors in being enablers or barriers to railway innovation is demonstrated in this light.

(4) Regulatory Requirements

The railway is a safety-critical industry and one that can have a significant environmental impact. Stringent safety and environmental regulations can require innovation to ensure effective compliance. The Office of Rail and Road (ORR) is the regulatory body for the UK railway and enforces safety standards, ensuring that rail companies to adopt advanced safety technologies and operational procedures.

Regulatory requirements can be drivers for innovation to ensure positive, effective compliance. Such requirements can also act as barriers, for example by establishing a high bar for introducing new technologies onto the railway.

(5) Brexit Impacts

The UK's withdrawal from the European Union has had an impact on many areas, including the railway sector. There have been changes in trading relationships, regulations, the availability of skilled researchers and workers, and, significantly, the availability of research and innovation funding. Prior to Brexit, the UK railway had been effective in building successful collaborations with European partners to secure significant investment in rail R&D and innovation projects, led by Network Rail and several universities including the Universities of Birmingham, Huddersfield and Southampton. The reduction in available public research and innovation funding has been felt by UK railway researchers (noted by several key actor interviewees in Groups 'SI' and 'ST' – see later).

Brexit has introduced challenges to the UK railway innovation landscape, such as trade barriers and supply chain disruptions, as well as impacting the transfer of innovative products and services. While not insurmountable, there are certainly additional impacting factors from Brexit that have not helped the UK railway when it comes to innovation.

In summary, the influence of external political factors are significant due to the railway's role as a public good, and its reliance on large quantities of public investment as well as the support and goodwill of the Government. This creates a strong political focus on the performance of the railway and a direct correlation between the level of that performance and the level of political support and goodwill.

4.2.2 Economic: External factors driven by the economy

Economic factors and conditions significantly impact the capacity for innovation within the railway sector.

(1) Public Sector Investment

As discussed above, the railway is reliance on major public sector investment to operate and maintain current services and capacity, as well as the availability of further capital investment to renew and upgrade the network to enhance services for customers. The need for this scale of infrastructure investment puts pressure on public finances, and in the current climate, that is a very real pressure.

While government funding remains committed to the railway (for example, major rail projects such as High Speed 2 and the TransPennine Route Upgrade are committed and delivery continues), the impacts of economic downturns and inflation can strain public budgets, limiting the level of funding available for large-scale innovation projects.

(2) Impact of inflation and period of economic stagnation/austerity

The impact of inflation, caused by higher energy prices, can have a very real impact the UK railway innovation landscape. In 2021, the electricity price rises caused a number of Freight Operating Companies to put their electric traction into storage and revert to diesel, this included Freightliner who withdrew their entire fleet of 23 mainline electric locomotives due to the electricity cost increase making operation of the locomotives uneconomic (RAIL Magazine, 2021).

Fluctuations in economic conditions create investment uncertainty, which can create sufficient risk or concern to delay the adoption of innovative solutions. However, economic upturns can incentivise recovery plans that include investment in infrastructure, offering opportunities for the adoption of innovations.

(3) High Operating Costs

Railways are expensive assets to operate and maintain. These significant operating costs create tangible incentives for greater efficiency in operations and therefore a real demand for innovation.

The increase in energy prices (discussed above) have increased operational costs for freight and passenger rail operators, which in turn drives demand for energy-efficient solutions, such as route and driving optimisation, along with demand for electric traction solutions to reduce dependency on fossil fuels.

(4) High costs (and financing) of R&D/Innovation

Both the development of new solutions, and their implementation and deployment onto the railway, are expensive activities. These high costs pose challenges, especially for smaller suppliers in the railway supply chain. The level of risk involved in innovation, who takes the burden of risk (compared with who receives the benefits), and incentives to encourage the acceptance of such risk, are key factors in the level of supply of innovation.

Innovative financing models, such as green bonds and investment funds, are becoming more common to enable product development and innovation activities.

From the literature review, Rothwell's five generations of innovation process are informative here. The first generation was supply-driven, and the second was demand-driven; however, the third generation came in the 1970s at the time of economic depression and the oil crises. At this point, business organisations focused on a balanced approach to investing in innovation, considering the level of risk against the opportunity for reward. In addition, the theory of innovation systems also highlights the importance of the interested network of actors and institutions who have a stake in seeing innovation happen, but where the costs and benefits may not be aligned.

The importance of external economic factors on the railway are clear – public investment directly supports railway operations and improvements. Economic and political factors are very much aligned, and therefore there is a clear connection between political demands for improvements and performance then being linked to future ongoing investment.

4.2.3 Social: External factors driven by societal issues and influences

Social trends and public expectations directly influence the direction of, and demand for, innovation in the railway industry.

(1) Alternative to road transport

Increased awareness and demand for sustainable transport options, can drive demand for innovation. Public demand for greener, more sustainable transport services has increased pressure on the railway industry to reduce its carbon footprint.

Sustainable transport options are increasingly important for the travelling public and for local authorities and politicians. Increased recognition of the negative impacts caused by increased road traffic (congestion, public health impacts, air quality etc) create demand for rail services, and opportunities for innovation that can encourage that modal shift.

The literature review investigated mission-oriented innovation and the use of policy instruments to drive innovation and change. Climate change and sustainable transport are a clear example of how public policy can be used as an instrument to promote changes in behaviour, changes in technology, and the interplay between them both.

(2) Passenger expectations

The development of new and improved services and offerings from all modes of transport has created increased customer expectations for better services, improved passenger information, real time updates, smart ticketing, and digital services, creating demand for innovation from the end-users. Customers on any mode of transport expect seamless travel experiences that make use of modern digital technologies and enhanced onboard connectivity during their journeys. Those expectations provide the case for investing and enabling innovation to support those demands.

There is a clear demand side expectation from end users to see the railway adopt innovative new technologies that can improve their experience on trains.

(3) Connectivity, accessibility, and social equity

There is increasing emphasis on making rail services more inclusive and accessible, and to provide the connectivity that everyone needs to go about their lives. Innovations in station planning and design, ticketing, as well as the onboard services available, are vital to equitably providing for the needs of all passenger demographics. These have driven demand for railway innovation to provide solutions that address particular accessibility needs.

(4) Increasing population and urbanisation

These megatrends have created the need to increase capacity and reliability to meet increasing demand on our transport networks, including the railway.

The UK's growing urban population intensifies demand for efficient and high-capacity rail services. Innovative solutions are required to address urban congestion and improve commuter experience on urban transport networks.

External social factors are hugely influential on the performance and demands on the railway. Considering the demand side of the railway industry in particular, the importance of providing attractive and competitive services is crucial in generating revenues and delivering both the economic return on investment and political return through ensuring that the railway is delivering on its role as a public good and critical national infrastructure network.

4.2.4 Technological: External factors driven by technological influence and developments

Technological advancements provide a vast array of opportunities for innovations that can deliver real benefits to the UK railway.

(1) Digitalisation

Recent developments in digital technologies have created new capabilities that can be positively applied to the railway. The advent of such technologies including artificial intelligence (AI), the internet of things (IOT), big data analytics, and cloud computing, can all play roles in improving railway operations and maintenance, most notably by driving down operating costs and driving up performance and reliability).

Just one example is the introduction of predictive maintenance, enabled by real-time data collection and analysis, which uses remote condition monitoring of assets to identify actual wear and running condition of systems, sub-systems, parts, and components, and can identify when inspection, maintenance, or replacement is actually needed, which optimises the asset's lifecycle and pre-empts issues from occurring during operation thereby reducing downtime and improving safety and reliability.

(2) Decarbonisation

Innovation delivering more sustainable traction systems for railway rolling stock can further enhance the railway's green credentials. With technology rapidly developing, innovation can enable the phasing out of fossil fuels (with the development and application of hydrogen and battery technologies for example), as well as utilise digital technologies that can simulate train performance to optimise energy consumption and efficiency. A number of these railway innovation projects are discussed later in the research.

(3) Smart Infrastructure

Sensing technologies can identify issues before they cause disruption enabling proactive action to be taken. Deployment of smart sensors and digital signalling systems can improve both the monitoring and utilisation of railway capacity, reducing disruption and improving service reliability.

(4) Automation and robotics

The use of automation and robotic technologies can deliver improvements in both safety and reliability in the maintenance of infrastructure and trains, as well as more efficient driving that can increase track capacity and efficiency use of railway assets.

Taken together, technological development can provide huge improvements to the planning, operation and maintenance of the railway system. The need for innovation is clear to generate and prove the potential applications of these technologies, but technological developments can also create complexity in terms of the new legal requirements that are brought about.

Taking all these potential technological advances for the railway together, there is a clear need to consider several models of innovation.

Firstly, Chesbrough's model of open innovation is important considering the ongoing development, testing, trialling, and deployment of a number of these technologies, such as digital signalling and traffic management. These technologies are systems with OEMs who are supplied sub-systems and components by their respective supply chains, generating significant requirements for development, system integration, testing, and validation. Given the demand side expectations to procure and implement these systems (Kessel 2023), and the time and resource requirements that are required, the need to collaborate closely with suppliers in order to develop and deploy major new technologies is critical. This point is also reflected in the fourth and fifth generations of Rothwell's innovation process which emphasise the importance of integration with suppliers and networked innovation respectively.

Secondly, the neo-Schumpeterian theory of innovation systems is helpful in highlighting the importance of actors and institutions. Kessel (2023) makes clear that the Office of Rail and Road, as the regulatory body, has given a clear signal to the industry that digital signalling must be implemented on the UK railway. This can be seen as one actor creating the demand for the innovation system to collaborate to develop the new technology and support its diffusion onto the UK railway system.

Thirdly, this can also be seen through the lens of the multi-level perspective framework. From the landscape perspective, the need for a more reliable railway that can extract additional passenger and freight capacity using digital signalling technology is viewed as required, and the regulatory body puts pressure on the socio-technological regime (the railway industry) to make the preparations to enable this technological transition to happen.

Finally, the significant concurrent roles of innovation supply, demand for innovation, and the roles of a wider set of actors and institutions, can all be seen in action as factors in enabling or blocking railway innovation

4.2.5 Legal: External factors driven by the law and the legal system

Legal considerations can and will play a significant role in shaping innovation strategies in the railway industry, particularly with the advent and introduction into application of new technologies.

(1) Safety-critical rail operations

As a safety-critical industry, the railway is strictly regulated and managed, with a comprehensive set of standards used to ensure that any product, system, part, or component, with any kind of interaction with the operating railway needs to be approved before it is put into use. The approvals and standards regimes create real barriers to entry for new products and services.

Correspondingly, health and safety controls can incentivise innovation to support the objectives of the regulatory regime

(2) Legal obligations, requirements, and protections

As discussed above, the development of new technologies, products, and services generate huge opportunities, but they also create novel challenges and questions that need to be considered and understood in application.

Four such examples include:

a. General Data Protection Regulations (GDPR) - The rise of digital technologies necessitates strict adherence to data protection laws. Innovations in passenger data management must comply with the GDPR.
b. Intellectual Property (IP) – Ensuring an effective regime that can protect IP is critical for enabling and incentivising innovation. Clear legal frameworks for IP generate the confidence to encourage investment in R&D by safeguarding proprietary knowledge and technologies.
c. Competition - UK competition laws influence collaboration and competition among rail companies, affecting how innovative technologies are developed and adopted. They also interact with procurement rules to ensure that products and services are purchased from the market in a fair and transparent manner.
d. Procurement – Procurement rules can provide a real barrier to innovation by stifling the ability for innovation demand to access the purchase of innovations.

External legal factors can play a significant role in influencing UK railway innovation. On one hand, they can be a key enabler by providing the structure for investment, procurement, and new technology deployments. However, their ability to act as a barrier, particularly when it comes to the assessment and enablement of novel technologies and applications being introduced onto the railway is apparent.

4.2.6 Environmental: External factors driven by the environment, environmental issues and concerns

Environmental sustainability is a both a huge opportunity and an urgent requirement for innovation in the railway industry.

(1) Climate change

Climate change is a significant mega-trend driving all kinds of incentives to innovate, with railway traction systems being just one example. The UK's long-term Net Zero legal requirements ensure that rail will have a key role to play as a sustainable form of transport for large numbers of people and goods.

The legal requirement to deliver net-zero emissions by 2050 also compels the railway to innovate to implement low-carbon solutions – not just by developing these technologies, but also how to implement them as efficiently and effectively as possible.

(2) Environmental impact of the operating railway

The UK railway can effectively utilise innovation to meet, and improve on, legal requirements to minimise noise and air pollution and deploy quieter, cleaner technologies and infrastructure designs and operation.

(3) Climate change adaptation and resilience

Extreme weather events have significantly impacted the railway, creating a need for innovation to provide mitigation and protection against them. These events, such as flooding and heatwaves, necessitate the design and implementation of resilient infrastructure, or else undertaking adaptation of existing infrastructure using innovative design to ensure it can stand up to such events as they become more commonplace.

Innovative construction materials, built-in resilience, and climate-adaptive designs are all critical for future-proofing the railway to maintain reliable operations.

(4) Sustainability in construction and materials

Innovations in sustainable materials (for example, developing and using alternatives to mitigate or replace the use of concrete) and energy-efficient construction methods (for example, zero emission vehicles) can reduce the lifetime environmental impact of railway infrastructure.

Additionally, increased use of recycling and circular economy practices are increasingly being adopted in railway projects and operations.

The importance of external environmental factors and the potential influence on UK railway innovation will be discussed throughout the research. The impact of climate change, and the potential role for the railway as a sustainable mode of transport, creates a clear opportunity for railway innovation to gain support and momentum to be delivered.

4.3 Analysis of Factors Internal to the Railway Industry

The PESTLE analysis highlights a range of external factors impacting the UK railway innovation landscape but does not directly draw out the internal factors that influence and impact innovation.

The UK Railway Safety and Standards Board have identified four such factors (RSSB 2017), which are: the fragmentation of the railway industry, a project culture focused on outputs, risk aversion, and the complexity and resource required to get product approvals.

Fragmentation of the industry

In the PESTLE analysis, the external political factors included political interests and priorities is aligned with the internal factor identified by RSSB of the fragmentation of the industry. The structure of the rail industry is impacted by political decision-making – as identified earlier in the research, industry reform is frequently announced, and taking advantage of innovation is usually cited as an opportunity that can be realised from this.

Industry fragmentation can be considered as the competing roles and interests of multiple actors and organisations across the railway, where those multiple roles can generate either conflicts or vacuums that produce a sub-optimal outcome. It can also generate a misalignment between where responsibilities and costs lie on one hand, versus where opportunities and benefits may be generated and delivered.

Project culture focused on outputs

The UK railway is output focused as it is measured by tangible deliverables – its projects, such as infrastructure maintenance and upgrades, or the delivery of a new fleet of trains into services, or the building of the High Speed 2 railway system. Project success is judged by being on time and on budget and by meeting the agreed specification, the outputs are set and agreed at the start of the project and are what the project is judged on thereafter.

This focus on outputs leads to delivering the precise specification and therefore removes any opportunities or incentives to use innovation to deliver a better outcome, as this generates unnecessary risk to the delivery of the project.

Risk aversion

Building on the previous point, the level of risk appetite can be a substantial barrier to innovation. The railway is an expensive industry with high capital costs and long lead times for planning and investment. Innovation requires a level of risk to develop new products or services that *could* generate future benefits against the existing state of the art. But the existing state of the art is known and understood, tried and tested, and therefore a lower risk to deploy on the operational railway.

From the perspective of demand for innovation the risk of utilising an innovative product or service is not just in the procurement and installation of the product (the resource and time to ensure it can be integrated into the system) but also the implementation and ongoing operation (will it be reliable in a challenging operating environment, given the significant risks if it is not).

Complexity of / resource required to obtain product approvals

By contrast, from the perspective of innovation suppliers, the railway is a huge challenge, as the RSSB have identified in the fourth factor. The time and resource required to obtain the requisite product and safety approvals just to enter the railway market are significant and create a substantial barrier to innovation. The access to, and use of, testing and validation facilities in a realistic operating environment to obtain such approvals is resource intensive.

Of the four factors identified by the RSSB as being significant internal factors impacting UK railway innovation, while the first is shaped by the political context, the other three are all a reflection of the culture and priorities of the railway industry. These four internal factors will be revisited as part of the data integration and analysis later in the research.

4.4 Chapter Summary

Figure 4.2 sets out a summary overview of the PESTLE analysis, which identified a range of external factors from across the six areas that play a role in influencing and impacting the UK railway innovation landscape.

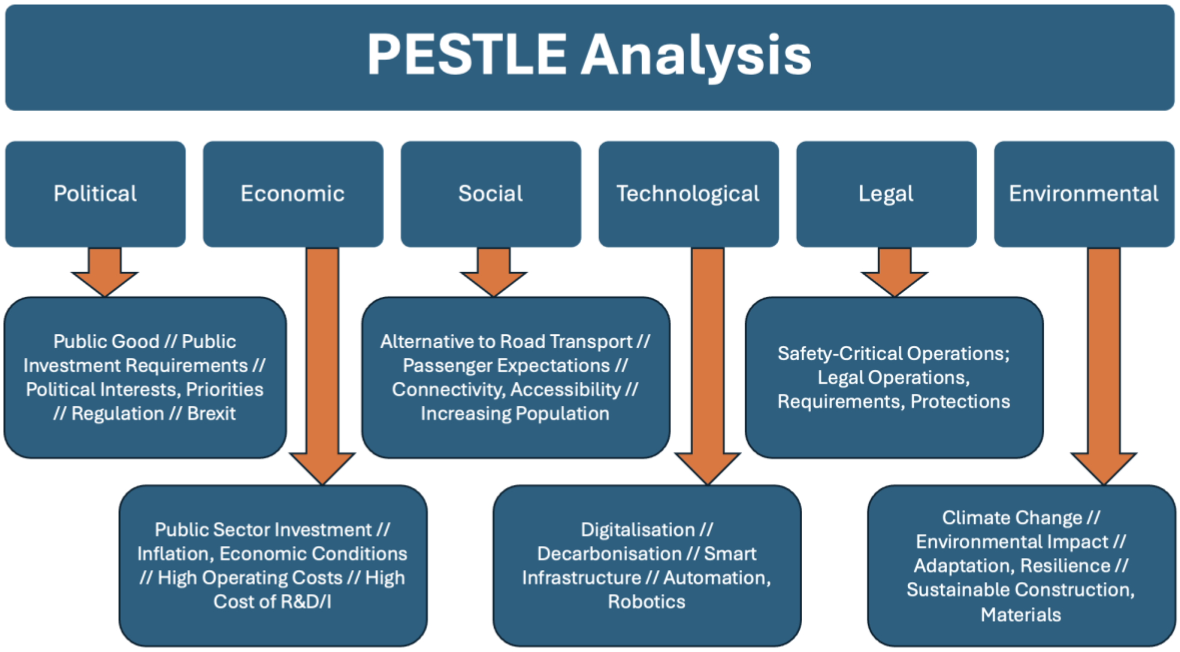

Figure 4.2: Summary of external factors identified by the PESTLE analysis

These six external groups of factors cover a range of influences on railway innovation, and these can vary in impact over time due to a range of circumstances, such as the political party in Government, the economic conditions, the priorities of the electorate, and contemporary issues influencing society (for example public safety, air pollution etc).

The four internal factors to the railway provide a valuable insight and taken together with the external factors, provide relevant data to inform the observation and analysis.

Chapter 5: Observation and Analysis (Quantitative Data)

Chapter Structure

5.1 Introduction

Data is a prerequisite to provide raw material for analysis that can be converted into the new knowledge that is sought as the purpose of the research. The scientific method for the pursuit of knowledge requires the collection of data from studies and experiments; that data is then analysed in the context of the research, from which the new knowledge is then derived (Ott, Longnecker, 2010).

As discussed in the previous chapter, the first of the two key sources of primary data for this research was an online survey. The purpose of collecting the quantitative data was to provide one of several necessary datasets to then conduct the research analysis concurrently using a critical approach. The design and evaluation of survey questions is vitally important to achieve the best quality data outputs from the survey (Fowler & Cosenza 2012).

5.2 Survey Design

The design of the research survey considered how to achieve a set of responses that were unbiased in both how the questions were asked and how the results could be interpreted, to provide as accurate a set of descriptive responses as possible (Kelley-Quon 2018). Fowler and Cosenza have identified four basic characteristics of questions and answers to enable effective survey data collection: (1) the questions must be consistently understood by the respondents; (2) the respondents need to be able to answer the questions with the requisite knowledge; (3) the respondents need to be able to answer the question effectively; and, (4) the respondents must be willing to answer the question (Fowler & Cosenza 2012).

The survey responses were pre-coded, and the majority of questions used a Likert scale to provide respondents with a simple methodology for recording their responses on a single idea at a time (Nemoto & Beglar 2013). The questions were written in a short, simple style with as little technical vocabulary as possible for ease of uniform comprehension, recognising that respondents would have a base knowledge of the UK railway innovation landscape.

The Likert scale response option for questions seeking perspectives on the phenomenon of rail innovation provided five options, as fewer than five would not produce a stable set of responses (Weng 2004), and verbal anchor labels were added to the response options as well to provide enhanced confidence and stability in the responses (Weng 2004).

The Likert scale response option for comparative questions used three options plus a 'don't know' option to provide sufficient stability in the responses while seeking to elicit sufficient clarity from the outputs.

The flow of questions was set out in a logical order for respondents to work through as easily as possible, using Microsoft Forms to provide a simple design for respondents to engage with quickly and effectively on either their computers, tablets, or smartphones.

5.3 Sample Population

The objective for the survey was to collect quantitative data on the UK railway innovation landscape. To do this, the technique of non-probability sampling was selected as a real-life phenomenon was the subject matter of the survey (Taherdoost 2016). The target sample population was identified as having sufficient knowledge of the UK railway innovation landscape to be able to provide knowledgeable responses that would provide valuable perspectives into the quantitative data.

The sample population were approached through the researcher's existing network, through direct email contact and via the researcher's LinkedIn profile, while encouraging contacts to encourage other appropriate respondents to take part. This method of 'snowball sampling' (Taherdoost 2016) generated 202 responses during the three-week period that the online survey was open.

5.4 Analysis of Quantitative Data from Online Survey

The Survey was published online using Microsoft Forms and was open for three weeks. The link to the Survey was shared directly via email with the researcher's network of industry contacts. It was also published and shared on the researcher's LinkedIn profile.

The Survey was designed and tested to take no more than ten minutes for respondents to complete and was structured and drafted to be easy to quickly comprehend and respond to. The Survey comprised 17 questions, set out in table 5.1 along with the response design for each question.

Q	Question Text	Response Design
1	On a scale of 1 to 5, how innovative do you think the UK railway industry is?	Likert scale 1-5
2	How innovative do you think the UK railway industry is compared to other countries' railway industries?	Likert scale 1-3 + don't know
3	How innovative do you think the UK railway industry is compared to the automotive industry	Likert scale 1-3 + don't know
4	How innovative do you think the UK railway industry is compared to the aerospace industry	Likert scale 1-3 + don't know
5	How innovative do you think the UK railway industry is compared to the maritime industry	Likert scale 1-3 + don't know
6	How familiar are you with the concept of 'railway innovation'?	Likert scale 1-5
7	Which areas of the railway sector do you believe are currently undergoing the most innovation?	Choose up to 3 from 8 options (including 'other')
8	On a scale of 1 to 5, how important do you think the following factors are in driving innovation in the railway industry?	Likert scale 1-5 for each of 7 options
9	What do you think are the biggest barriers to innovation in the railway industry?	Choose up to 3 from 9 options (including 'other')

10	In your opinion, which area of railway innovation will have the most significant impact over the next 10 years?	Free text
11	How prepared do you think the railway industry is to adopt new innovations?	Likert scale 1-5
12	What role do you believe the railway industry should play in addressing environmental and sustainability challenges through innovation?	Free text
13	Have you or your organisation been directly involved in developing and/or implementing railway innovations?	Yes/No
14	If you answered Yes to Q13, please describe the nature of your involvement in railway innovation projects.	Free text
15	What do you believe is the most important factor for accelerating innovation in the railway sector? If you would like to share any further thoughts about railway innovation, then please do so here.	Free text
16	What is your role in the railway industry?	7 options (including 'other')
17	How many years of experience do you have in the railway industry?	5 time period options

Table 5.1 Summary of online survey design

The Survey was designed to flow through three Parts:

Part 1 – Contextual Questions (1-6), that all used Likert scale response options to provide a base context for responses providing a comparative overview of the UK railway innovation landscape.

Part 2 – Technical Questions (7-15), these questions were more open to allow for respondents to give more detail on their perspectives of the UK railway innovation landscape.

Part 3 – Respondent Questions (16-17), these questions sought to provide a general insight into the respondent types, asking for their broad area of activity or expertise in the railway industry, and their length of time working in the sector.

The responses to the Survey are set out and described below, following the format of the Survey.

5.4.1 Contextual Questions

The first six questions were designed to provide a broad overview of respondents' perspectives of the UK railway innovation landscape. These questions sought to provide a comparative baseline to illustrate a broad, quantitative overview of how the UK railway innovation landscape appears to those who are involved in some way and have at least some familiarity with it.

Question 1

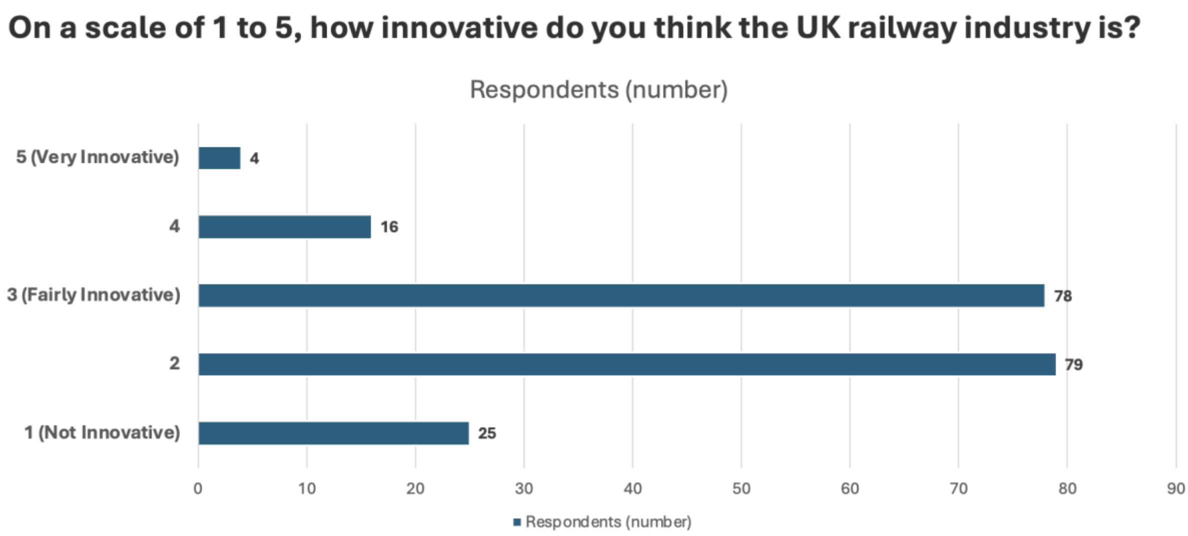

Figure 5.1: Responses to online survey question 1

This first question posed a simple opening statement for the respondents to consider – how innovative do *you* think the UK railway is - with a Likert scale of five response options to provide a generic overview, and the response is striking. As shown in figure 5.1, out of 202 responses in total, only 20 respondents (just under 10%) answered with one of the two positive options (5 or 4), while 104 respondents (52% - a simple majority) answered with one of the two negative options (2 or 1). The remaining 78 respondents answered with the middle option (3, fairly innovative).

Question 2

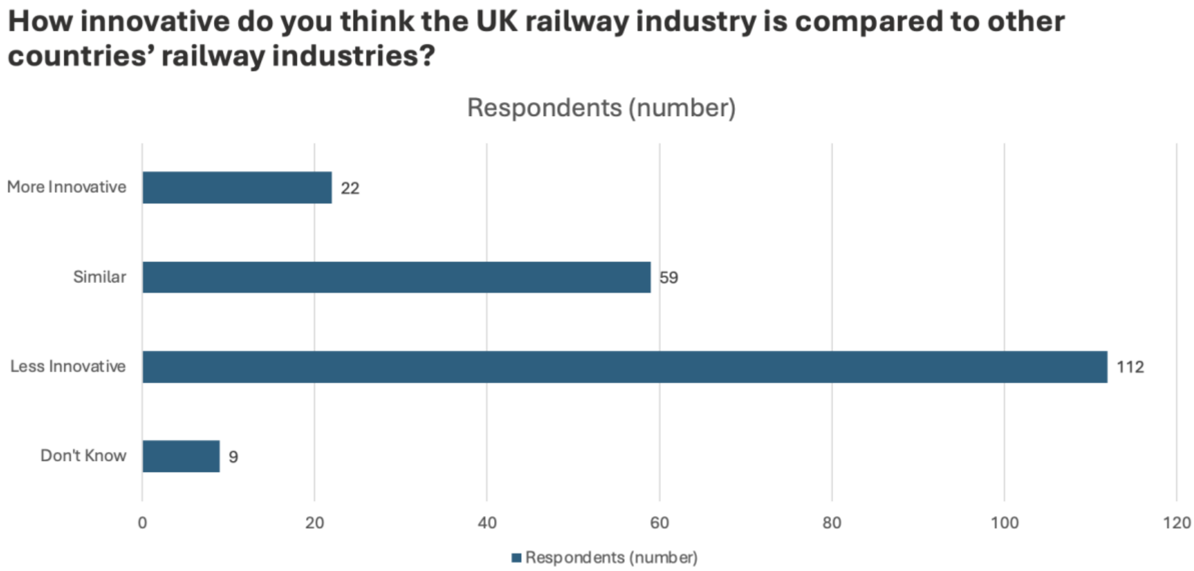

Figure 5.2: Response to online survey question 2

This second question sought to build on the premise of the first question and also provide a comparator baseline by considering the UK railway against other countries' railway industries. Figure 5.2 shows that the responses are challenging to the UK railway, with 22 responses (approximately 10%) saying more innovative and 112 (approximately 55%) saying less innovative.

From the responses to the first two questions alone, the quantitative survey data has validated the research problem that the UK railway innovation landscape is struggling to support and enable innovation.

The following three questions (qs. 3-5) provided further comparator baseline data, building on question 2 and referring to the earlier research investigation of three adjacent transport sectors – automotive, aerospace, and maritime.

Question 3

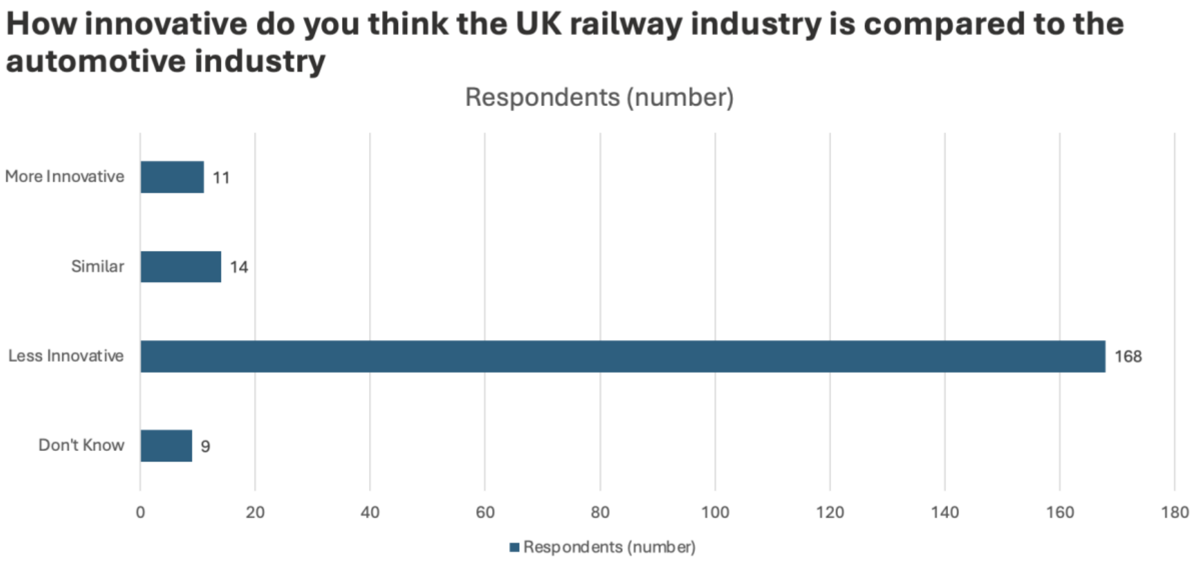

Figure 5.3: Response to online survey question 3

The responses to question 3, shown in figure 5.3, were emphatically of the majority opinion (approximately 83%) that the automotive industry is more innovative than the railway industry in the UK.

A key difference between the industries is in how they generate profits which plays a significant role as either an incentive or a barrier. Railway vehicles are high capital cost and relatively low volume, with low upfront cost and proven technology being priorities in new vehicle procurements. Those procurements are run by public bodies with strict procurement rules and public money being invested. For a railway rolling stock manufacturer, keeping those purchase costs down will increase the likelihood of sales and profit. For automotive manufacturers, cars are high volume commodities with shorter asset lifetimes. The cars are sold direct from the manufacturer to the end user, the private driver generally, and the focus is on both the upfront cost but also the lifetime cost, value, and reliability (Winnett et al 2017).

These market conditions provide an incentive for automotive manufacturers to innovate to drive profits, whereas for rail manufacturers there are strong incentives to play safe and avoid innovation in preference for the known and tested existing technologies.

<u>Question 4</u>

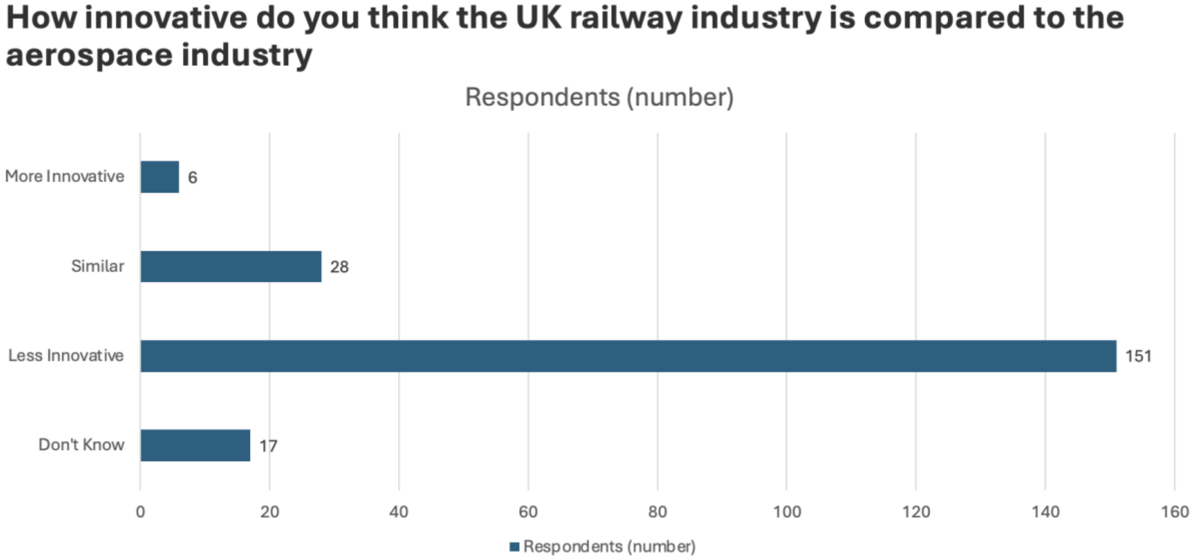

Figure 5.4: Response to online survey question 4

The responses to question 4 closely follow the previous question with approximately three-quarters of respondents considering the aerospace industry to be more innovative than the railway industry, shown in figure 5.4.

<u>Question 5</u>

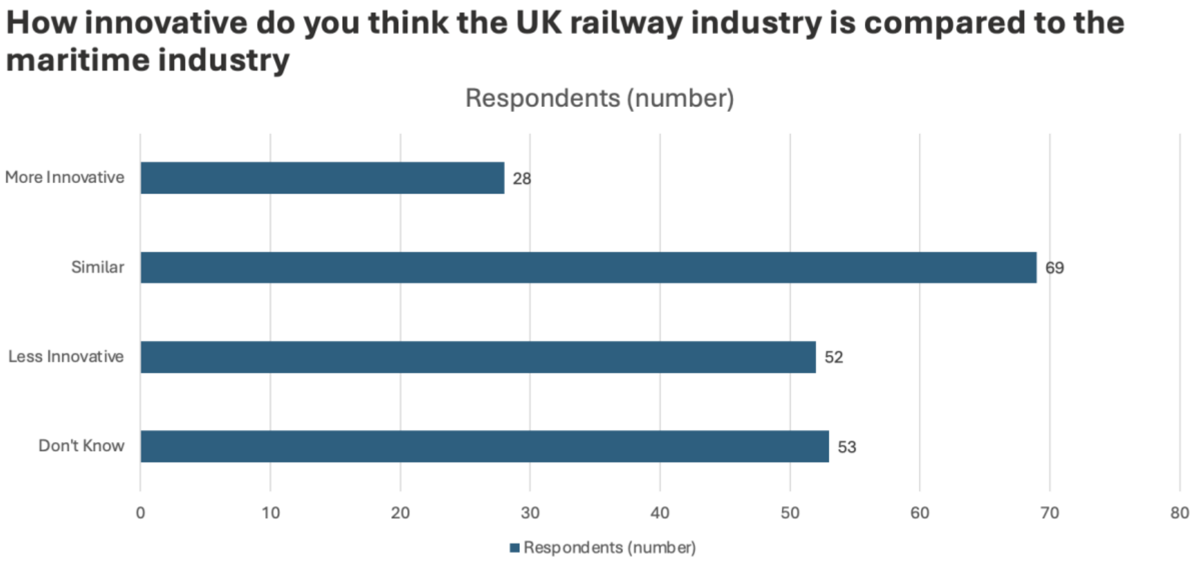

Figure 5.5: Response to online survey question 5

The third industry comparison question differed from the previous two. With a quarter of the respondents answering 'don't know' about innovation in the maritime industry, and the largest response (just over one-third) answering 'similar', shown in figure 5.5. However, of the remaining 80 responses, the majority responded that the railway was less innovative than maritime.

Overall, across these three industry comparison questions, the UK railway industry was very firmly viewed as less innovative than these adjacent transport industries.

Question 6

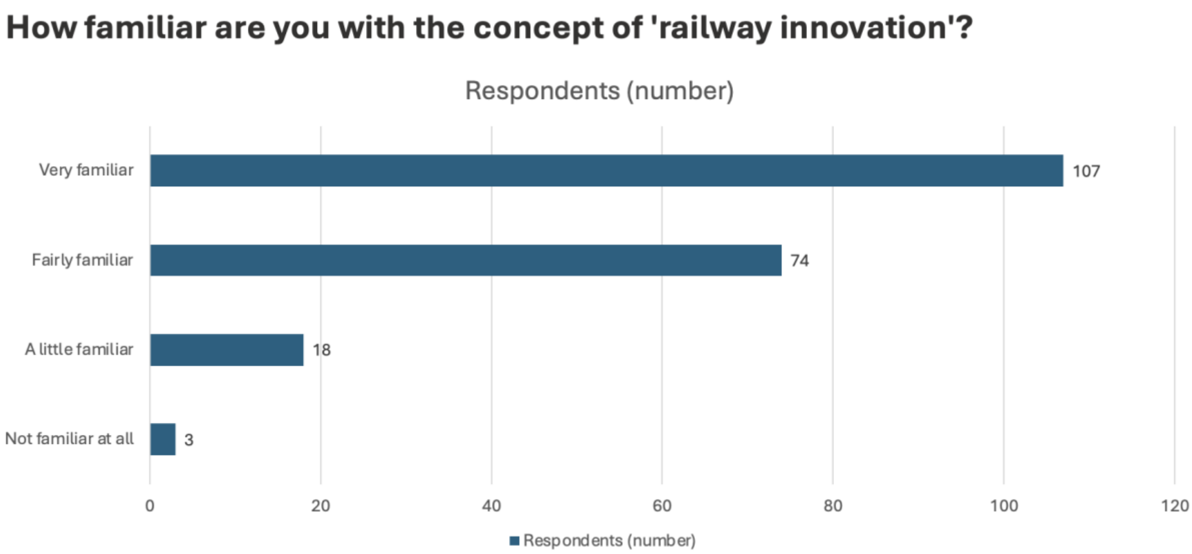

Figure 5.6: Response to online survey question 6

The final contextual question in the Survey provided a bridge from the context to the concept of rail innovation. Illustrated in figure 5.6, the majority of respondents (53%) responded that they were *very* familiar with the concept of rail innovation, and a further 37% responded that they were fairly familiar. This provided validation that the technique selected to obtain the sample population for the Survey - using non-probability (snowball) sampling (as discussed above) – was the correct approach to get a statistically valid sample population in terms of both volume of responses (sufficient number to describe the real life phenomenon) and quality of responses (sufficient knowledge of the phenomenon to describe it purposefully for the benefit of the research).

5.4.2 Technical Questions

Building on the contextual questions at the beginning of the Survey, this Part posed a set of questions that were more open to allow respondents to give more detail on their perspectives of the UK railway innovation landscape.

Question 7

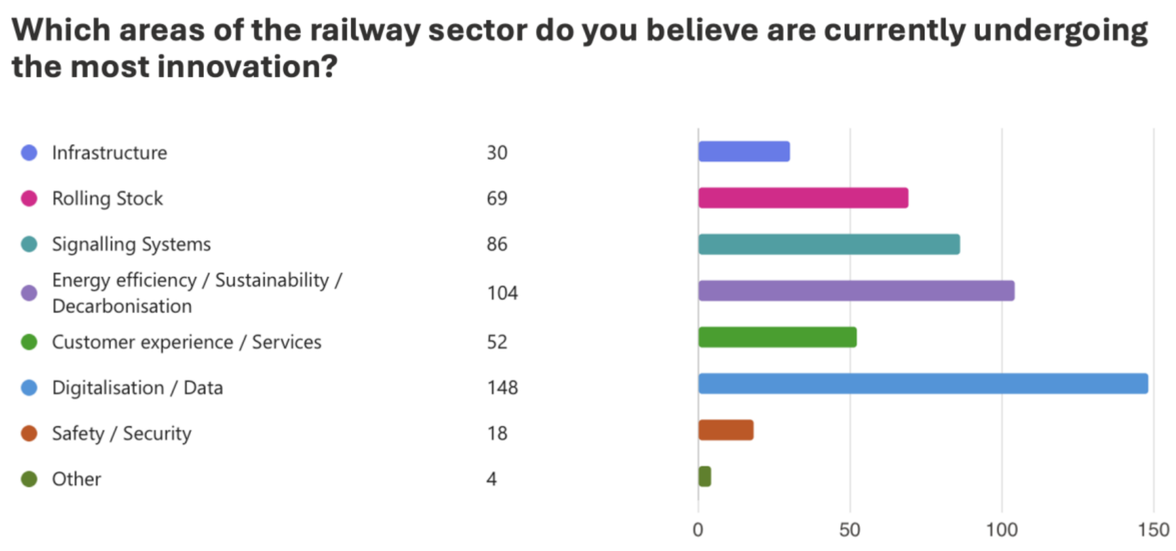

Figure 5.7: Response to online survey question 7

Question 7 was designed to gain insights into the subject matter of railway innovation and identify where current efforts in the UK railway innovation landscape are focussed. Respondents could select up to three responses from a choice of seven innovation areas with an eighth option of 'other' including free text if required. The responses are shown in figure 5.7.

The top two areas for innovation identified by respondents were digitalisation / data (73%) and energy efficiency / sustainability / decarbonisation (52%).

Question 8

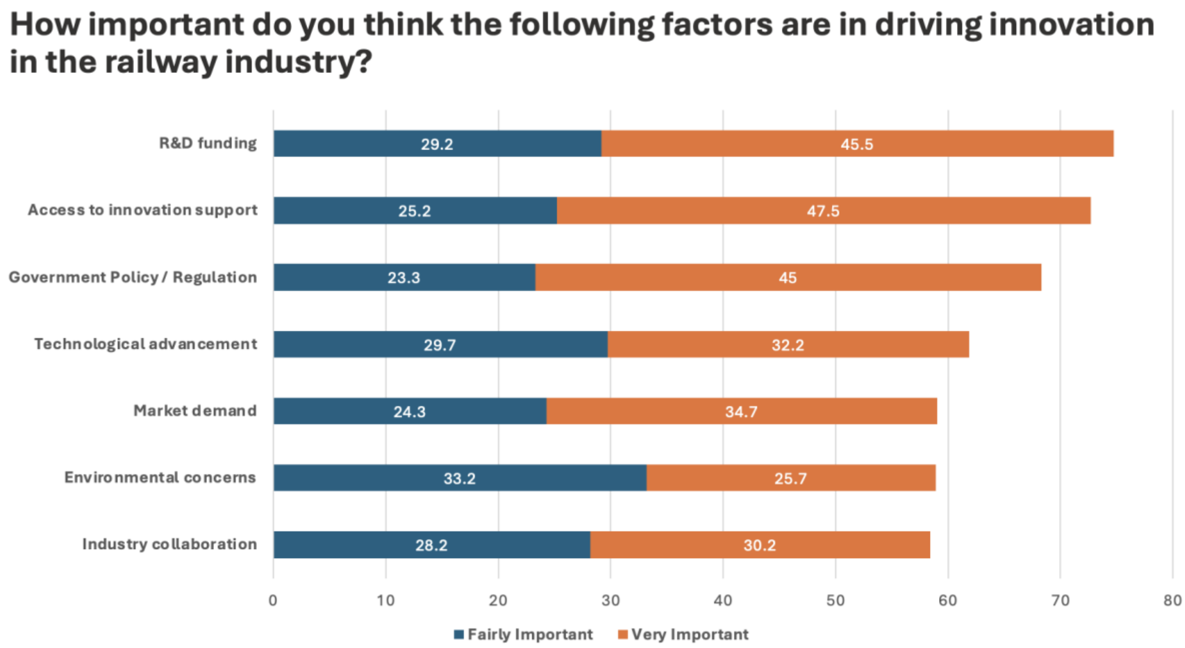

Figure 5.8: Response to online survey question 8

Question 8 gave a list of seven potential factors driving railway innovation with respondents invited to use a Likert scale of five responses to rate each of them. The top two response options (i.e. 5 Very Important and 4 Fairly Important) have been highlighted and added together to rank these factors in order of respondent preference. Figure 5.8 sets out those responses.

This question provides an innovation supply-side perspective – what are the factors that can motivate or incentivise railway innovation to happen. The top two factors (both scoring over 70%) were funding and access to innovation support (which included testing and validation); the third factor was Government policy and regulation with 68%. Interestingly, the advancement of technologies as a driver by creating opportunities for innovation supply was fourth (61%) while market demand for innovation was just below (59%).

Question 9

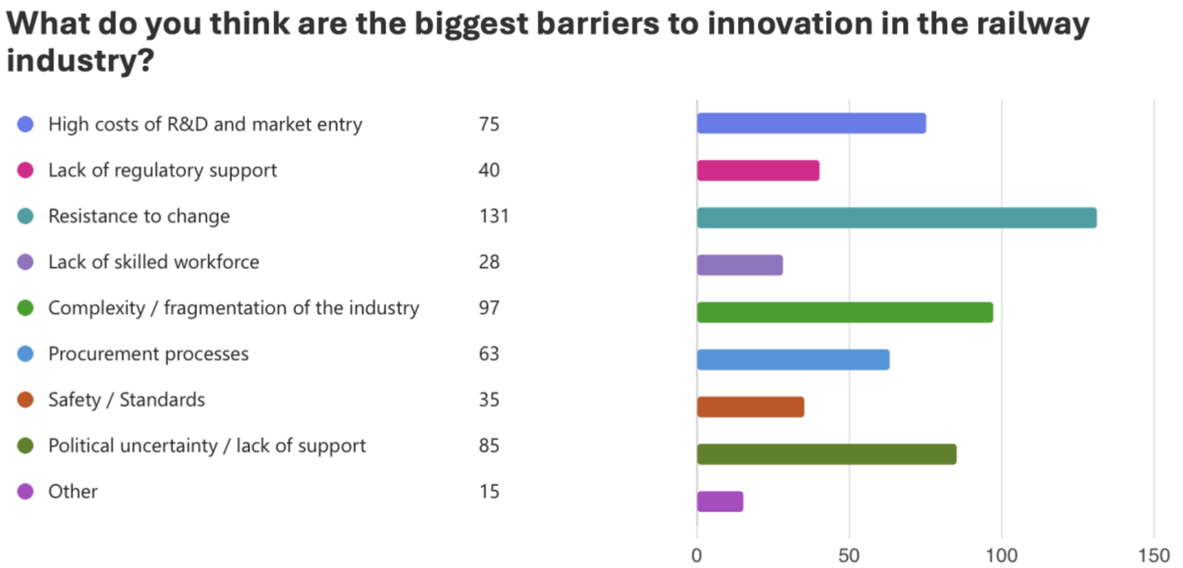

Figure 5.9: Response to online survey question 9

This question asked respondents to consider the biggest barriers to innovation and select up to three options from the list which included 8 options plus a further option for 'other' with free text.

Referring back to the PESTLE analysis of external factors influencing rail innovation (see section 4.2), and internal factors to the railway industry (see section 4.3), we can categorise the above responses:

High costs of R&D / market entry	External factor - economic Internal factors - risk aversion; complexity/resource required to get product approvals
Lack of regulatory support	External factors - political; legal Internal factors - risk aversion; complexity/resource required to get product approvals

Resistance to change	Internal factor - industry culture
Lack of skilled workforce	External factors - political; economic
Complexity / fragmentation of the industry	External factor - political Internal factor - fragmentation of the railway industry
Procurement processes	External factors - political; legal Internal factor - risk aversion
Safety / standards	External factor - legal Internal factor - complexity/resource required to get product approvals
Political uncertainty / lack of support	External factors - political; economic
Other – these responses included the list below; these have also been categorised: Unnecessary/complex legacy systems and proprietary standards (*External factor – legal*) Design For Reliability requirements (*Internal factors – culture; complexity / resource to get product approvals*) Bureaucracy and slow decision-making (*Internal factors – culture; risk aversion*) Standards not keeping up with technology (*Internal factors – culture; risk aversion*) Difficulty testing/validating innovations (*Internal factors - culture; risk aversion; complexity / resource to get product approvals*) Coordination of multiple suppliers (*External factor – legal; Internal factor – fragmentation of the railway industry*) Sector is heavily skewed towards OEMs, Tier 1s, large consultancies and against innovative SMEs (*External factor – Economic; Internal factors – fragmentation of the railway industry; culture; risk aversion*)	

Industry is averse to risk (*Internal factor – risk aversion*)
Lack of engineering stubbornness/freedom to investigate (*Internal factors – culture; risk aversion*)
All of the above!

Table 5.2: Categorisation of responses to online survey q.9

The top five responses selected by respondents as one of their options were:

Resistance to change (131 / 65%)

Complexity/fragmentation of the industry (97 / 48%)

Political uncertainty/lack of support (85 / 42%)

High costs of R&D and market entry (75 / 37%)

Procurement processes (63 / 31%)

<u>Question 10</u>

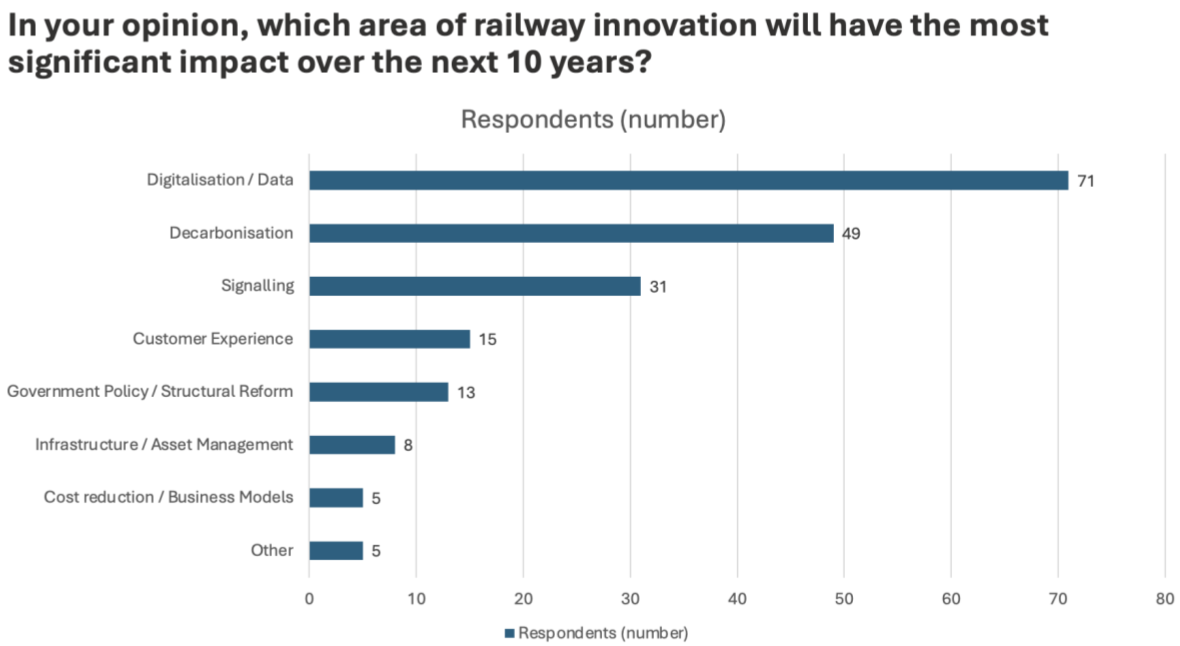

Figure 5.10: Response to online survey question 10

This free text question asked, ‘In your opinion, which area of railway innovation will have the most significant impact over the next 10 years?’. Figure 5.10 shows the 197 responses that were given, these were then analysed and then grouped together with the results set out in table 5.3.

Coded groups of results	**Number of responses (%)**	**Indicative responses**
Digitalisation / Data	71 (35%)	These results also included references to Artificial Intelligence, Internet of Things, Remote Sensing and Monitoring, Digital Twins, and Automation.
Decarbonisation	49 (24%)	These results included sustainable traction, hydrogen, battery, energy efficiency, and climate change adaptation.
Signalling	31 (15%)	This included digital signalling, traffic management, European Train Control System (ETCS), Communication Based Train Control (CBTC), and Automatic Train Operation (ATO).
Customer Experience	15 (7%)	This included improved rolling stock, stations, ticketing, and high-speed rail.
Government Policy / Structural Reform	13 (6%)	This included railway reform, financing, public policy, renationalisation, removing the fragmentation of the industry, and investment in rail R&D/Innovation.
Infrastructure / Asset Management	8 (4%)	This included effective maintenance and improved reliability.
Cost Reduction / Business Models	5 (2%)	This included business model innovation, and whole life cost assessment.

Other	5 (2%)	These included testing and trialling facilities, rail freight sector, switches, new materials, and entrants to the industry.
Total free text responses given	197 (98%)	

Table 5.3: Analysis of responses to online survey q.10

Question 11

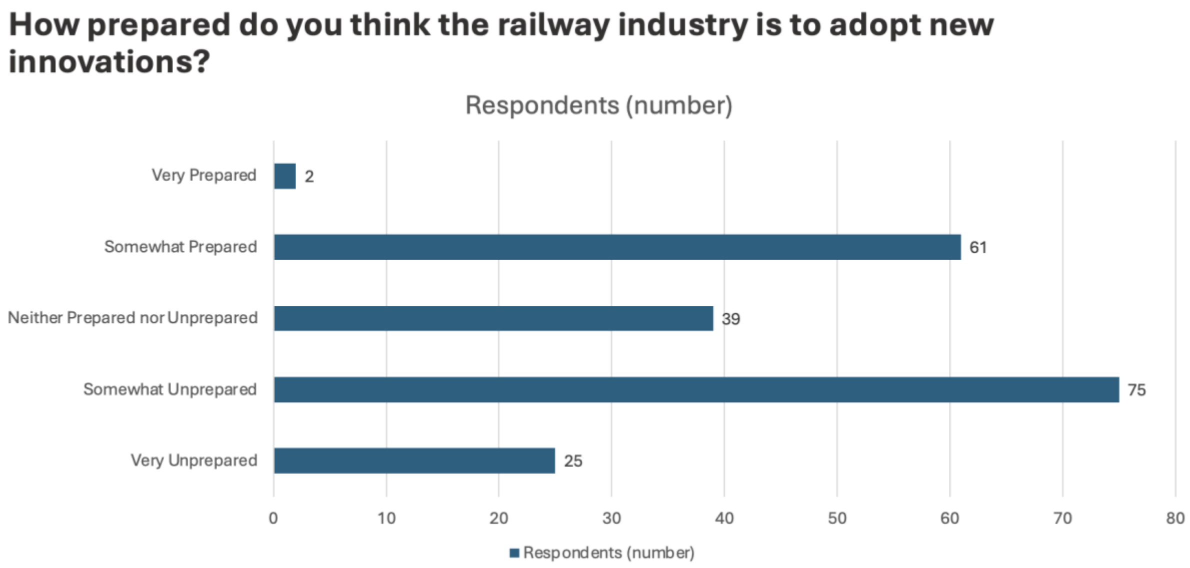

Figure 5.11: Response to online survey question 11

This question posed a relatively simple question for the respondents to consider – how prepared do *you* think the UK railway is to adopt new innovations - with a Likert scale of five response options to provide a generic overview. Out of 202 responses in total, 63 respondents (31%) answered with one of the two positive options (5 or 4), while 100 respondents (*just* under 50%) answered with one of the two negative options (2 or 1), shown in figure 5.11.

On the other hand, this can be reported as 175 (86%) did not commit to either extreme and opted for the mid-ranking answers, from somewhat prepared to somewhat unprepared.

As a result, further qualitative data was sought to better understand and describe the current context for the UK railway.

Question 12

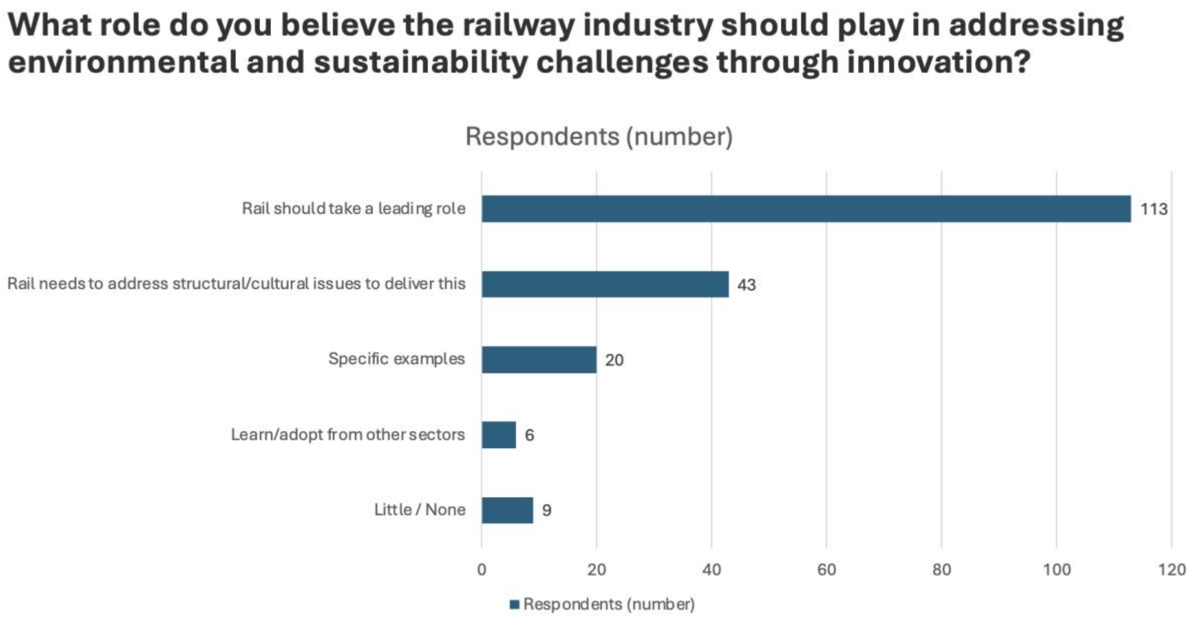

Figure 5.12: Response to online survey question 12

This free text question sought to elicit open responses from respondents on the potential role that the railway can play in supporting the environmental and sustainability challenges and policy objectives, such as the long-term Net Zero legal requirements established by the UK Government.

Figure 5.12 shows the 191 responses that were received for this question which were then been coded as shown in table 5.4.

Coded groups of results	**No. of responses (%)**	**Indicative responses**
Rail should take a leading role	113 (56%)	Responses included: rail already has - and should have - a leadership role as a relatively clean and sustainable mode of public transport for people and freight; modal shift was frequently mentioned as being key to this; as well as using innovation as a tool

		to improve environmental and sustainability performance.
Rail needs to address structural/cultural issues to deliver this	43 (21%)	Responses included: rail could be a leader but needed to address industry issues, most frequently the internal factors of structure and culture. References were made to collaboration, building partnerships, lobbying Government, supporting SMEs, not favouring OEMs/Tier 1s, revising procurement strategies to reflect needs/outcomes.
Specific examples	20 (10%)	These responses gave specific examples of what the railway could do to address environmental and sustainability challenges. Half of these responses specifically mentioned sustainable traction systems (including electrification, battery, and hydrogen systems). The remainder referenced climate change adaptation and resilience, noise, passenger information, ticketing, and park & ride.
Learn/adopt from other sectors	6 (3%)	These responses all stated that rail should learn from other sectors. Several added that the railway should adapted tested and proven innovations from other sectors to boost its own performance.
Little/None	9 (4%)	These responses all focused on the railway needing to focus on delivering core services before prioritising environmental and sustainability challenges and using innovation to address them.
Total free text responses given	191 (95%)	

Table 5.4: Summary of free text responses to online survey q.12

Question 13

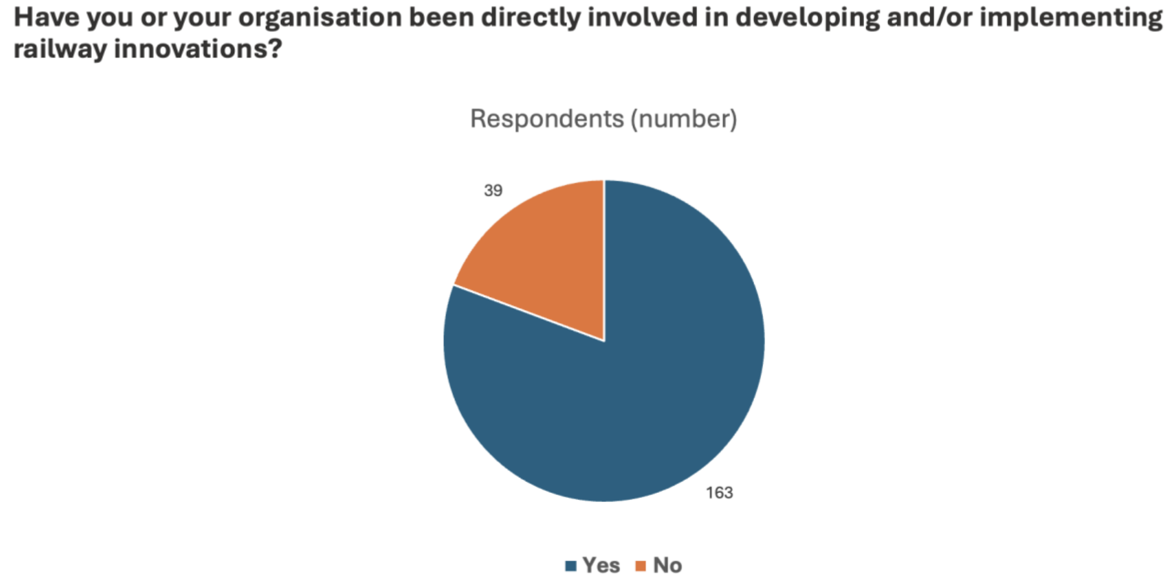

Figure 5.13: Response to online survey question 13

This direct question sought to draw out practical experience of developing and delivering railway innovations. Figure 5.13 shows a positive response from 163 respondents (81%) indicating that a significant proportion of the Survey's sample population had practical experience of undertaking railway innovation to inform their responses to the Survey.

Question 14

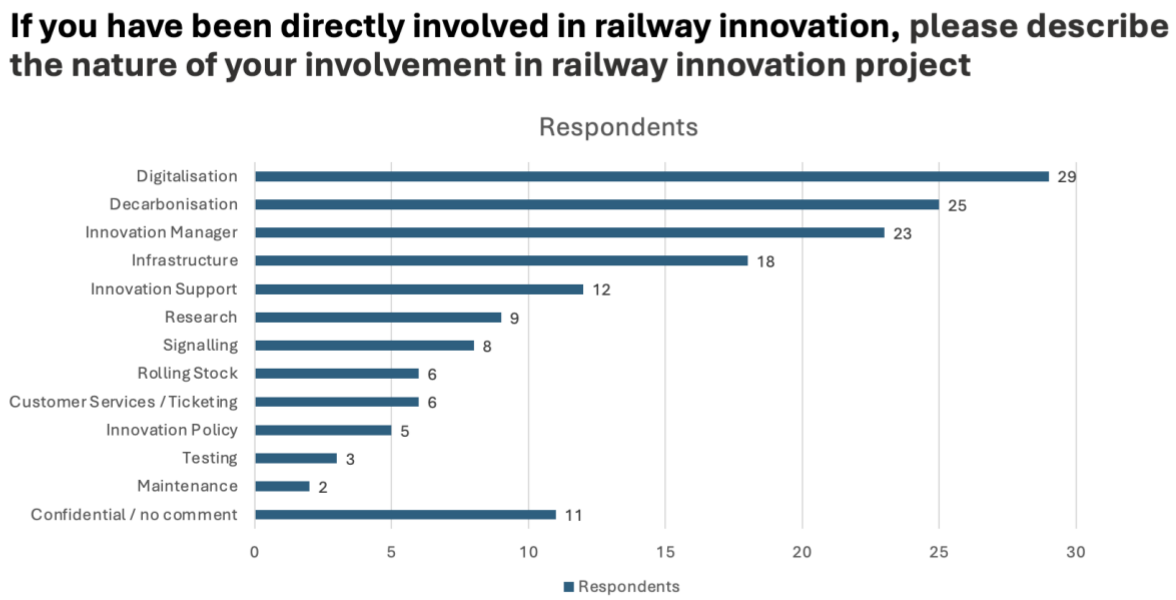

Figure 5.14: Response to online survey question 14

Respondents who answered yes to Question 13 were then asked to describe the nature of their involvement with innovation. Responses reflected a breadth of involvement with a blend covering either topics (i.e. purpose of innovation) or functions (i.e. type of role), shown in figure 5.14. Table 5.5 shows the top three response categories for both purpose and function.

Top 3 responses by category (purpose)	Top 3 responses by category (function)
Digitalisation (29 responses)	Innovation Manager (23 responses)
Decarbonisation (25 responses)	Innovation Support (12 responses)
Infrastructure (18 responses)	Research (9 responses)

Table 5.5: Top 3 response categories to online survey question 14

The responses were coded into categories reflecting either the innovation purpose or the functional role. In terms of functions, innovation manager was used to reflect innovation specialists leading or delivering multiple projects; innovation support was used to incorporate innovation specialists providing advice and support into companies and projects (for example, railway clusters and trade associations).

__Question 15__

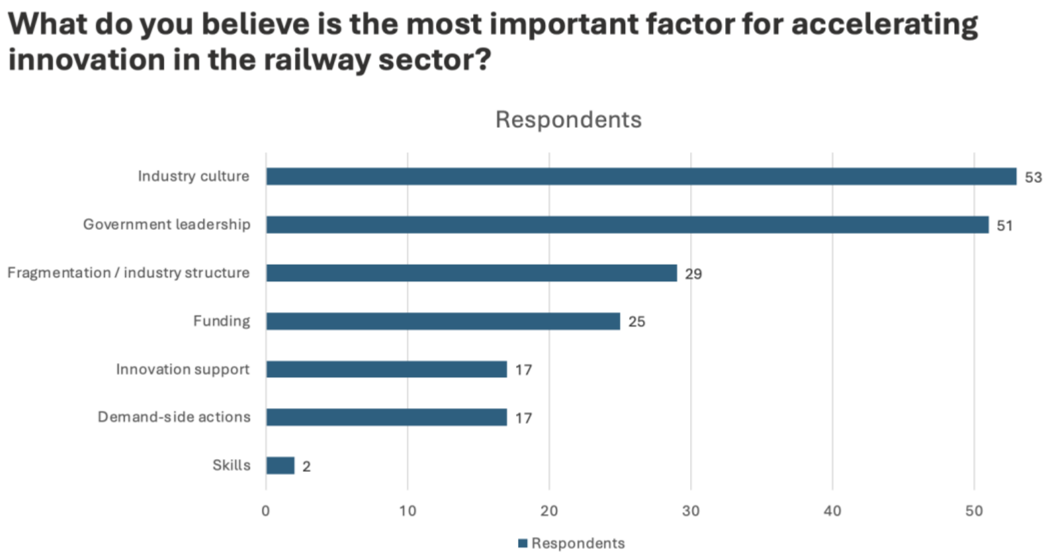

Figure 5.15: Response to online survey question 15

The last technical question sought to capture respondents' perspectives on where the key enabler/barrier to railway innovation exists. This question was phrased to identify the critical area that can enable more railway innovation to successfully happen. Figure 5.15 sets out the responses.

The two standout responses – industry culture (53 responses) and government leadership (51 responses) – make a very clear statement with one internal and one external factor (as identified earlier in this chapter) each being crucial. Additionally, the third most popular response - fragmentation / industry structure (29 responses) – is another internal factor, albeit framed by government policy and can be described as a hybrid factor.

The fourth and fifth most popular responses – innovation support and funding – can both be considered as supply-side issues where innovation supply needs the support to undertake and commercialise innovation projects more effectively. Demand-side actions included responses covering the railway being more open to using innovation, and procurement being a key barrier to innovations entering the market.

5.4.3 Respondent Questions

These final questions were posed to provide an insight into the respondents, asking for their broad area of activity or expertise in the railway industry, and their length of time working in the sector. These questions give us an understanding of the sample population and its consistency with our original target methodology for the Survey.

<u>Question 16</u>

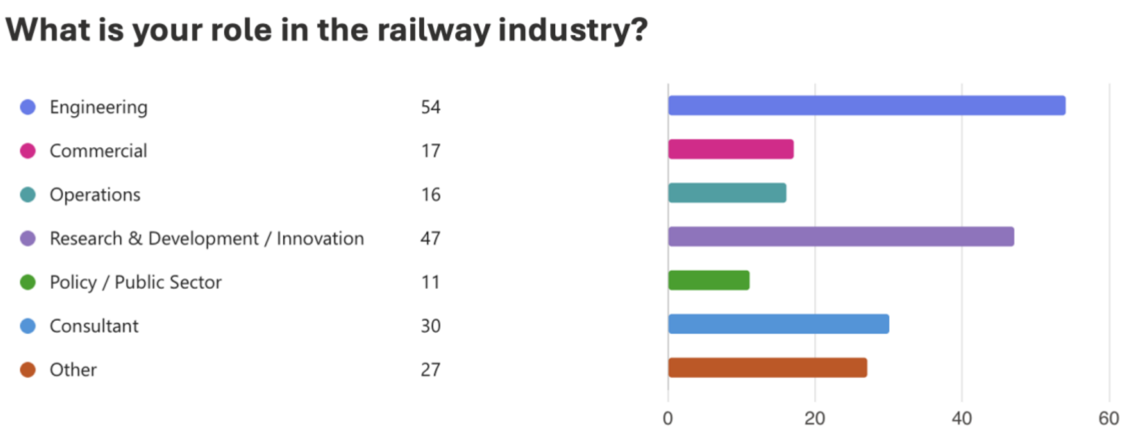

Figure 5.16: Response to online survey question 16

The first respondent question sought to understand the industry discipline area and knowledge of the respondents. The top two responses were engineering (27%) and research & development / innovation (23%).

Responses within the 'Other' category included: retired, advisor, project management, railway industry cluster manager, health and wellbeing, marketing, and public affairs.

Question 17

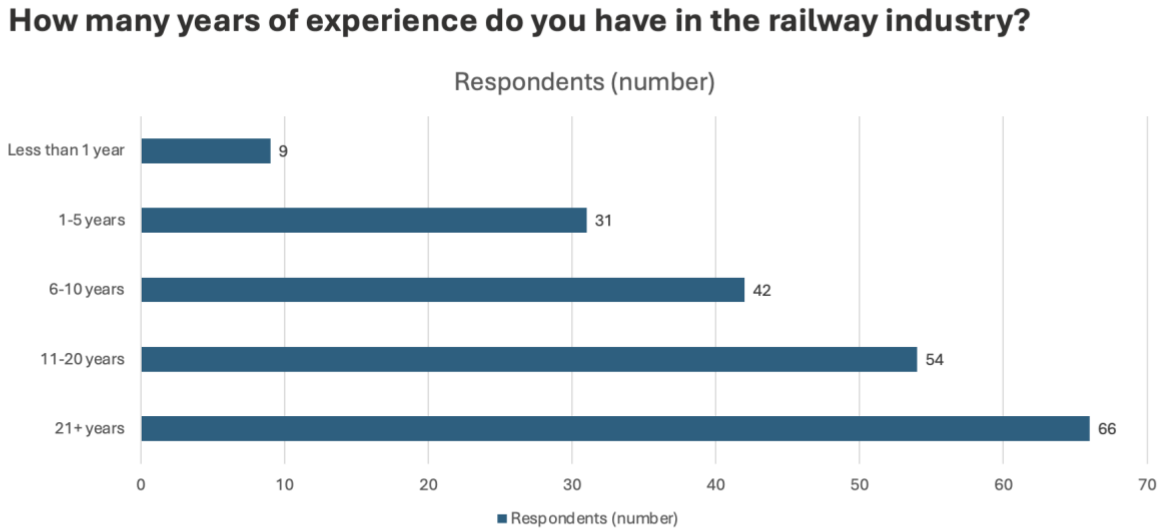

Figure 5.17: Response to online survey question 17

The second respondent question, and final Survey question, was designed to gain an understanding of the railway industry experience of the sample population.

From the 202 respondents who took part in the survey, 120 (59%) had over 10 years of railway industry experience, and 66 of those respondents (33%) in fact had over 20 years of experience in the industry.

5.5 Chapter Summary

The quantitative data collected through the online survey provides a high volume of relevant and valuable data to support this research. This dataset provides significant value in informing this research as well as future research. A number of key findings can be drawn out from the quantitative data that contributes to new knowledge in the field. The key findings are summarised in table 5.6 below.

Questions 1-5: assessment of UK rail industry innovation and comparative assessment with other railway industries and with three adjacent transport sectors	These datasets provide a valuable assessment from a relevant sample population of the UK rail industry's innovation capability and a comparative assessment with international rail industries and with three adjacent transport sectors. These datasets contribute new knowledge and insights and also provide an opportunity for further research.
Question 7: assessment of areas of the rail sector undergoing the most innovation	This dataset contributes new knowledge and insight into areas of the rail sector most open to innovation and where further research can provide relevant real-world impact and opportunity.
Question 8: assessment of most relevant factors that drive rail innovation	This dataset provides new knowledge and rich insight into the perceived drivers of innovation in the sector and provide critical value to this and future research in the field.
Question 9: barriers to rail innovation	This dataset provides new knowledge and rich insight into the perceived barriers of innovation in the sector and provide critical value to this and future research in the field.

Question 10: areas of future impact for rail innovation	This dataset provides an extremely valuable insight into where the future opportunities for relevant research and development lie for the railway. This contributes significant new knowledge and real value for researchers seeking to understand where research can contribute real impact to the sector in the future.
Question 12: the role of rail innovation in supporting environmental and sustainability challenges	This dataset contributes new knowledge and valuable insight into the perceived role of rail innovation in the field of decarbonisation.
Question 15: the most important factors to enable rail innovation	This dataset provides a valuable assessment identifying the key factors to enable UK rail innovation. This contributes new knowledge in the field and is key in supporting this research and future research opportunities in this field.

Table 5.6: Summary of key findings from quantitative data

Chapter 6: Observation and Analysis (Qualitative Data)

Chapter Structure

6.1 Introduction

Following on from the Survey, the second of the two key sources of primary data was the collection of qualitative data through interviews with key actors in the UK railway innovation landscape. Qualitative research can be undertaking collection of data to support the research project that manifests as narrative or non-numeric (i.e. non-quantitative) data as the result of the research (Carter and Henderson in Bowling and Shah (eds.) 2005). Qualitative research can be used to develop new theory, in contrast to quantitative research which can be effectively used to test hypotheses. This creates the opportunity to use both types of research in combination with qualitative research being used prior to quantitative data collection to form hypotheses, and after the quantitative data tests these hypotheses, to be used to dive into the outputs from the quantitative data analysis (Carter and Henderson 2005).

This research has used interviews with 43 key actors with knowledge of the UK railway innovation landscape to both develop the hypothesis and test it, and to form the construction of the conceptual framework that is the central objective of this research project.

6.2 Interview Design

Interviews are a pre-eminent means of collecting qualitative data, and when designed carefully, interviews can provide a rich set of data to inform the research project (Qu and Dumay 2011).

The design of interviews to collect qualitative data can take several formats. There are three different formats for interviews to take into consideration (Gall, Borg, Gall 2003; Qu and Dumay 2011; Taherdoost 2022) which are summarised below.

Informal conversational – an unstructured interview, where the interview is a relatively spontaneous free-flowing conversation. The unstructured and flexible approach allows the conversation to flow and to naturally probe, but on the other hand this makes recording and coding of the data less stable and clear.

General interview – a semi-structured interview, with a set of questions prepared but these can be deployed as appropriate by the interviewed depending on the content of the conversation. This allows the interviewer to add supplementary questions, and miss out others, as appropriate to suit the interview context. The flexibility of this approach allows interviewers to draw out the information being sought from the participants.

Standardised open-ended interview – a structured interview, using a fixed set of open-ended questions that allows interviewees to express themselves as they wish to provide their responses. This can remove any potential bias in the collection of the data but also risks missing out on collection of all data and being able to correctly code it.

The semi-structured approach was chosen to provide flexibility in approach, and to ensure that interviewees could be encouraged to provide as much insight as possible to the data collection for the research. This approach has been favoured for the research as it is best aligned with the critical approach, allowing the interviewer to understand and probe the interviewee using their choice of language and understanding of context to elicit data (Qu and Dumay 2011).

The interview format was prepared in advance to a standard structure utilising space for three types of questions – main questions, planned follow up questions, and spontaneous questions (Taherdoost 2022).

Interviewees were given a standard briefing in advance (see figure 6.1) to give them prior knowledge and understanding of the research intent and the purpose of the interview, a statement on the right to privacy and confidentiality, and the interview structure and main questions to be asked.

Research Interview Briefing Sheet

Many thanks again for agreeing to take part in this research interview. Your insights and perspectives on the subject of railway innovation will be hugely helpful to me in conducting my research on this subject for my PhD thesis.

In advance of the interview, you do not need to undertake any preparation whatsoever! I want to hear about your views, knowledge, and experience in the field. To give you an idea of what I would like to discuss with you, the interview will be structured around 5 main questions:

1. Why does the railway need innovation?
2. What does the UK railway innovation landscape look like to you?
3. Who are the key actors?
4. What are the main enablers/barriers to railway innovation?
5. What can be done to enable more innovation to happen?

There will be additional questions that I will ask as the interview progresses that will supplement these main questions.

I envisage the interview taking between 30 and 60 minutes, subject to the time available to us.

Statement on privacy and confidentiality

Participation is strictly anonymous, you will be undertaking this interview with me in confidence, and what you say will not be attributable to you in any way.

I will record what you say in notes that will not be attributable to you. The outputs from the interview will be anonymised, coded, analysed, and aggregated. I will ensure that you are not identifiable as your candid expression of views on the subject are of real importance to the research.

Many thanks again for your support with this research project.

Alex

Alexander BURROWS
Birmingham Centre for Railway Research and Education
School of Engineering
University of Birmingham

Figure 6.1: Research interview briefing sheet provided to all interviewees

The semi-structured interview format used for all interviews is set out in Figure 6.2. The five main questions were consistently asked to provide a structure for the conversations and to provide a baseline for all interviews to ensure a consistency of approach, while allowing for the interview conversations to be free flowing to draw out all relevant information from each of the interviewees.

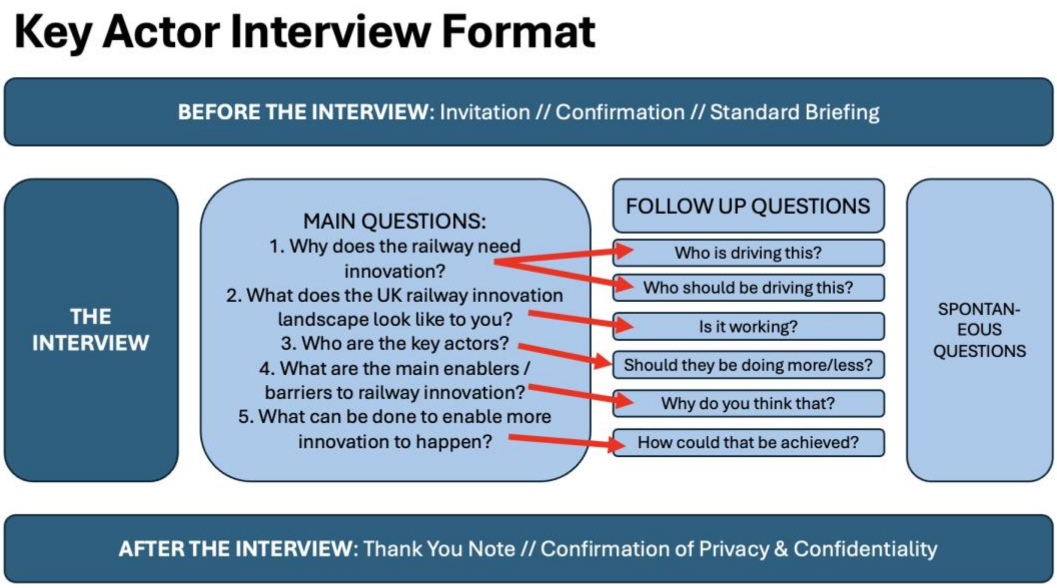

Figure 6.2: Diagram illustrating the process undertaken for key actor interviews

6.3 Interviewee Selection

These in-depth interviews were designed to collect qualitative descriptive data on the UK railway innovation landscape to support the research. Interviewee selection was undertaken to ensure a rich set of data could be drawn out from semi-structured interviews to address the research question (DiCicco-Bloom and Crabtree 2006).

As discussed in chapter 3, three core actor and stakeholder categories were identified to establish a minimum sample of key actors to interview. These categories were established to cover all relevant areas from across the UK railway innovation landscape, coming from across the railway supply (innovation supply) and operations (innovation demand) sectors, as well as from a third category of wider stakeholders and actors. These categories are summarised in figure 6.3.

Group 'SI' Supply Industry / Innovation Supply	Group 'OP' Rail Operations / Innovation Demand	Group 'ST' Stakeholders, Others
Rail supply industry actors including OEMs, Tier 1 contractors, SMEs, consultancies, ROSCOs, and the Department for Business and Trade (DBT)	Railway operating industry including Train Operating Companies, Freight Operating Companies, Network Rail, and the Department for Transport (DfT)	Trade associations, the railway sector trade press, international actors and organisations, and regulatory and advisory bodies

Figure 6.3: Three core actor and stakeholder categories for interviewees

Group 'SI' included individuals with a breadth of experience covering a wide range of actors from across the UK rail supply industry including railway rolling stock, systems and infrastructure manufacturers, infrastructure Tier 1 contractors, small and medium sized enterprises, rolling stock owning companies, consultancies, and the Department for Business and Trade as the sponsoring department of the rail supply industry within the UK Government. The breadth of this group (the largest represented of the three groups) included:

- Original Equipment Manufacturers (OEMs) / Tier 1 Contractors: The large organisations that manufacture the railway rolling stock and railway systems and deliver the railway infrastructure. At the top of the railway supply industry, their role in the UK railway innovation landscape is significant.
- Small and Medium sized Enterprises (SMEs): The engine room of the railway industry, SMEs are traditionally the root of much innovation, including in the railway sector.
- Consultancies: Several large consultancies play a major role in designing, engineering, and delivering the railway, with a range of smaller consultancy businesses in support. They provide strategic and technical consultancy support to most parts of the railway sector.
- Testing: Testing and trialling facilities are key to enabling innovation, access to them and their support is a key part of railway innovation.
- ROSCOs: The rolling stock owning companies, provide the financing that purchases new rolling stock from the OEMs and then lease the trains on to the Operating Companies.

Group 'OP' included individuals with a breadth of experience covering a wide range of actors from across the UK railway operations sector that includes operating companies for passenger and freight services, railway infrastructure managers (specifically Network Rail, who own and manage the vast majority of the UK's railway infrastructure), and the Department for Transport as the sponsoring department of the rail operations sector within the UK Government. The majority from this group included:

- Train/Freight Operating Companies (TOCs/FOCs): The organisations that run the train services for passengers and freight. Currently in the process of moving from private sector ownership back to the public sector as a part of Great British Railways (GBR), and to be re-integrated with railway infrastructure as Network Rail also joins into GBR.

Group 'ST' included individuals with a breadth of experience covering a wide range of actors from across the wider stakeholder environment that goes beyond the supply and demand sides of the UK railway innovation landscape. This includes:

- Regulatory: The Office of Rail and Road (ORR) as the regulator, and the Railway Safety and Standards Board (RSSB) as the body responsible for safety and the railway standards, as well as the coordinator for the railway R&D programme and roadmap.
- Trade Associations: The Railway Industry Association (RIA) and Rail Forum as the two largest trade associations representing the railway supply industry, and the Rail Freight Group representing the interests of the rail freight sector.
- International: international railway innovation experts to gain a comparative perspective of the UK railway innovation landscape. This includes international railway organisations, railway clusters, and the international railway trade press.

This research was lucky to have access to a range of relevant actors and stakeholders with suitable knowledge and experience. In total, forty-three interviews were held to collect qualitative data to supplement the online survey that collected the quantitative data from 202 respondents. The forty-three interviews all had a minimum of five years of experience working in and around the UK railway innovation landscape.

6.4 Analysis of Qualitative Data from Key Actor Interviews

6.4.1 Methodology for analysis of qualitative data

Prior to the completion of the forty-three key actor interviews, a methodology for structuring and coding the data outputs from the interviews was established. The outputs from the literature review and the PESTLE analysis were considered and informed this structuring. In addition, the design of the online survey was also considered to ensure sufficient coherence to enable the effective integration of the qualitative and quantitative data.

The standard structure for each of the interviews is set out in figure 6.4.

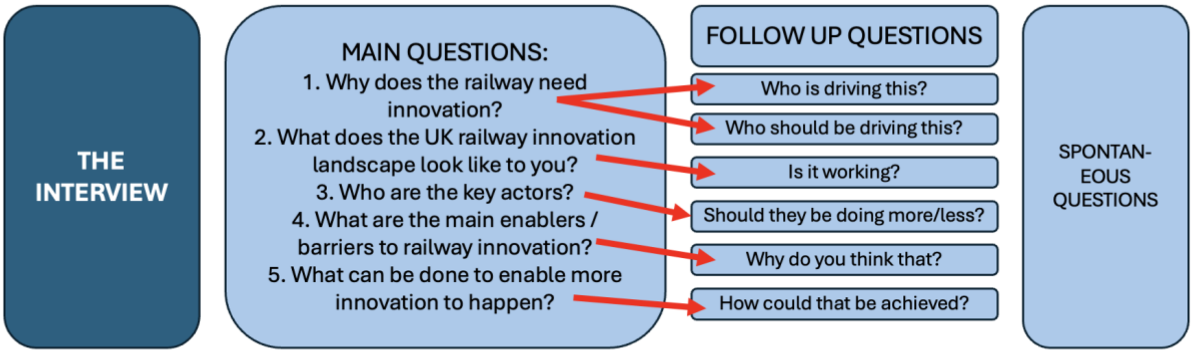

Figure 6.4: Standard interview structure

Each interview was based around the five main questions set out in figure 6.4, that provided the structure and flow. From those questions, several follow up questions were asked with additional spontaneous questions used as appropriate to enable the interviewee to express their thoughts and perspectives effectively.

The methodology for the analysis of the qualitative data follows the structure of the quantitative data collection and uses the two core parts of the online survey – contextual questions and technical questions.

Respondent questions were not required as the interviewees were selected based on a minimum requirement of five years of experience working in and around the UK railway innovation landscape. The interviewees were grouped into three core areas groups with the balance of the 43 interviewees shown in figure 6.5.

Group 'SI' Supply Industry / Innovation Supply	Group 'OP' Rail Operations / Innovation Demand	Group 'ST' Stakeholders, Others
Rail supply industry actors including OEMs, Tier 1 contractors, SMEs, consultancies, ROSCOs, and the Department for Business and Trade (DBT)	Railway operating industry including Train Operating Companies, Freight Operating Companies, Network Rail, and the Department for Transport (DfT)	Trade associations, the railway sector trade press, international actors and organisations, and regulatory and advisory bodies
21 Interviewees	**12 Interviewees**	**10 Interviewees**

Figure 6.5: Overview of the forty-three interviewees by category

The interview discussions have been analysed with the responses coded and grouped to enable a quantitative overview of each of these main questions – these are summarised below.

6.4.2 Analysis of qualitative data

The first three main questions were contextual questions with the aim of drawing out further description and analysis of the UK railway innovation landscape:

- Why does the railway need innovation?
- What does the UK railway innovation landscape look like to you?
- Who are the key actors?

Figure 6.6 shows the coded responses to the first main question that opened all of the interviews. Interviewees unanimously responded directly with the need to improve railway operations i.e. providing better services for passengers and freights, and all bar one mentioned the need to reduce costs. The need for using innovation to compete with other modes of transport and the effective exploitation of new technologies were also raised frequently, while climate change was the fifth most frequently mentioned response to this question.

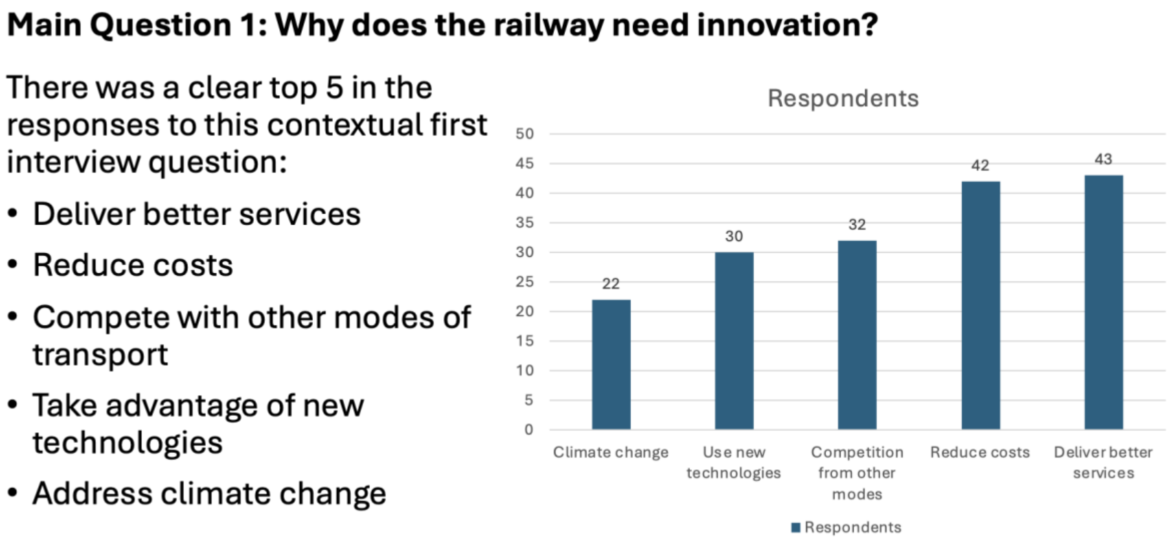

Figure 6.6: Overview of responses to Main Question 1

Figure 6.7 shows the coded responses to the second main question about perceptions of the UK railway innovation landscape. The vast majority of respondents were negative and most frequently commented on the fragmentation of the industry and the lack of coordination and joining up of efforts to deliver the best outcomes from innovation activities. Railway reform was mentioned by half of the interviewees as a reason to hope that change might happen but concerns over funding and procurement processes tempered these hopes.

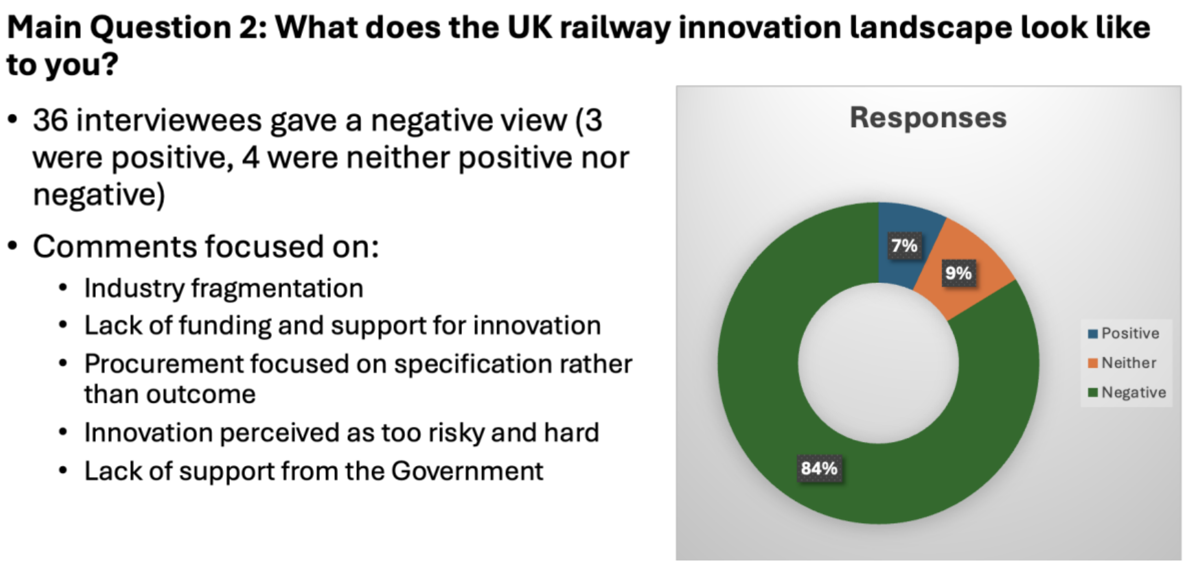

Figure 6.7: Overview of responses to Main Question 2

Figure 6.8 sets out responses to the third main question – who did interviewees perceive to be the key actors in the UK railway innovation landscape. Unsurprisingly, the major buyers of innovation – the Government, Network Rail, and other client bodies (such as High Speed 2, East West Rail, Transport Scotland, Transport for Wales, Transport for London), came out on top. They were followed by the train and freight operating companies, the original equipment manufacturers, and small and medium-sized enterprises – as the suppliers of innovation. Moving down, universities were mentioned by half of the interviewees, and then the Office of Rail and Road and the Railway Safety and Standards Board.

One interesting observation to note was that the European Union, through the Horizon funding and the Europe's Rail Joint Undertaking, was mentioned more often than Innovate UK, the UK Government's innovation funding agency (14 and 10 interviewees respectively).

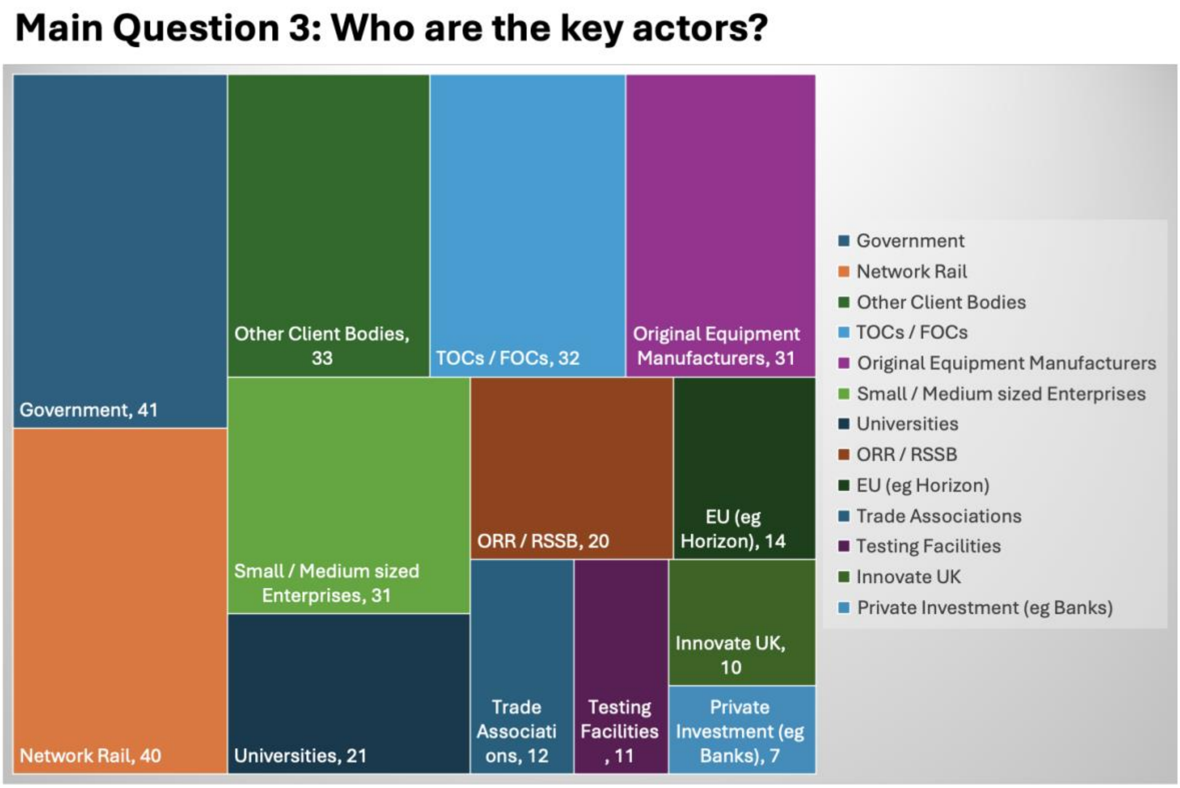

Figure 6.8: Overview of responses to Main Question 3

The fourth and fifth main questions were technical questions. The aim for these was to move from descriptive analysis to a more considered reflection and expressing subjective views and perspectives on how the UK railway innovation landscape is and how it could be improved:

- What are the main enablers/barriers to railway innovation?
- What can be done to enable more innovation to happen?

Figure 6.9 shows the coded responses to Main Question 4 that sought to identify interviewees' perspectives on the main enablers and barriers to railway innovation. The structure and fragmentation of the industry was the most frequent response, closely followed by the culture of the industry, the role of Government, and the availability of funding. The industry's appetite for risk in supporting and investing in innovation was also frequently mentioned and this was coded separately from industry culture to reflect a very strong set of responses from the majority of interviewees on this specific point.

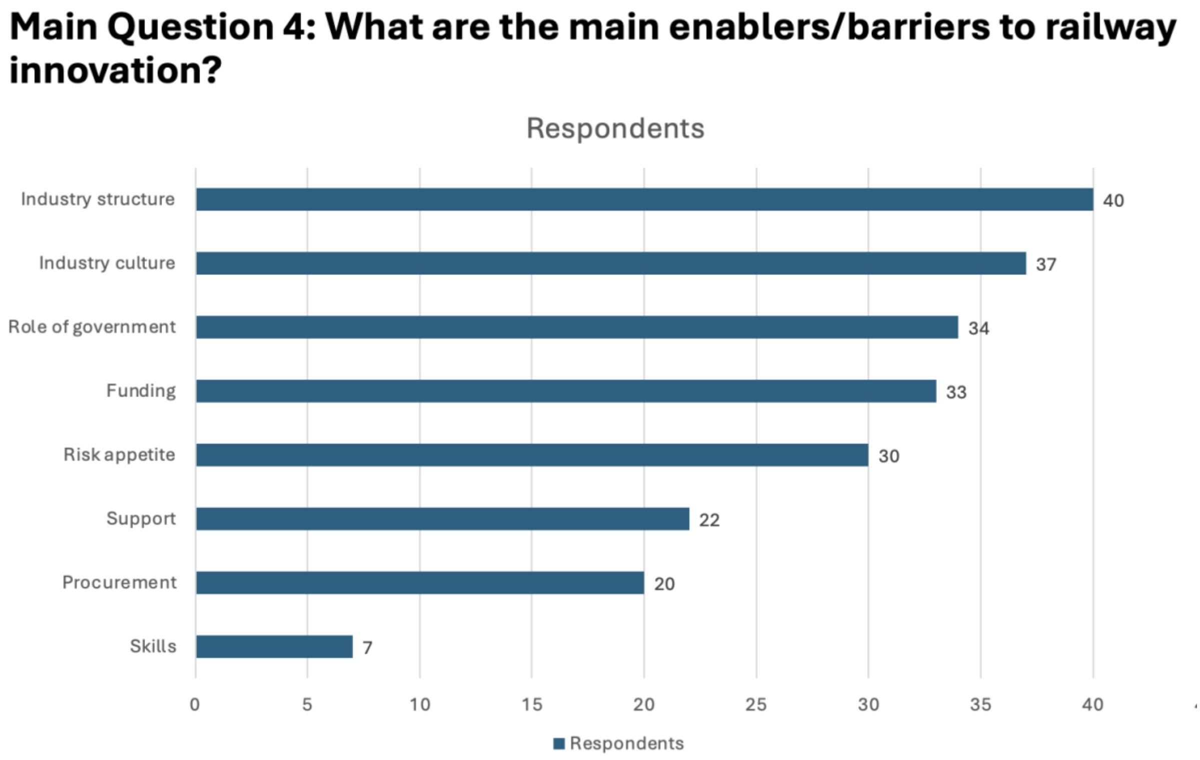

Figure 6.9: Overview of responses to Main Question 4

Figure 6.10 summarises the coded responses to Main Question 5 that asked interviewees for a forward-looking response to what could be done to enable more innovation to happen. The responses were consistent with previous questions, with industry reform, government leadership, and funding all mentioned by the clear majority of interviewees.

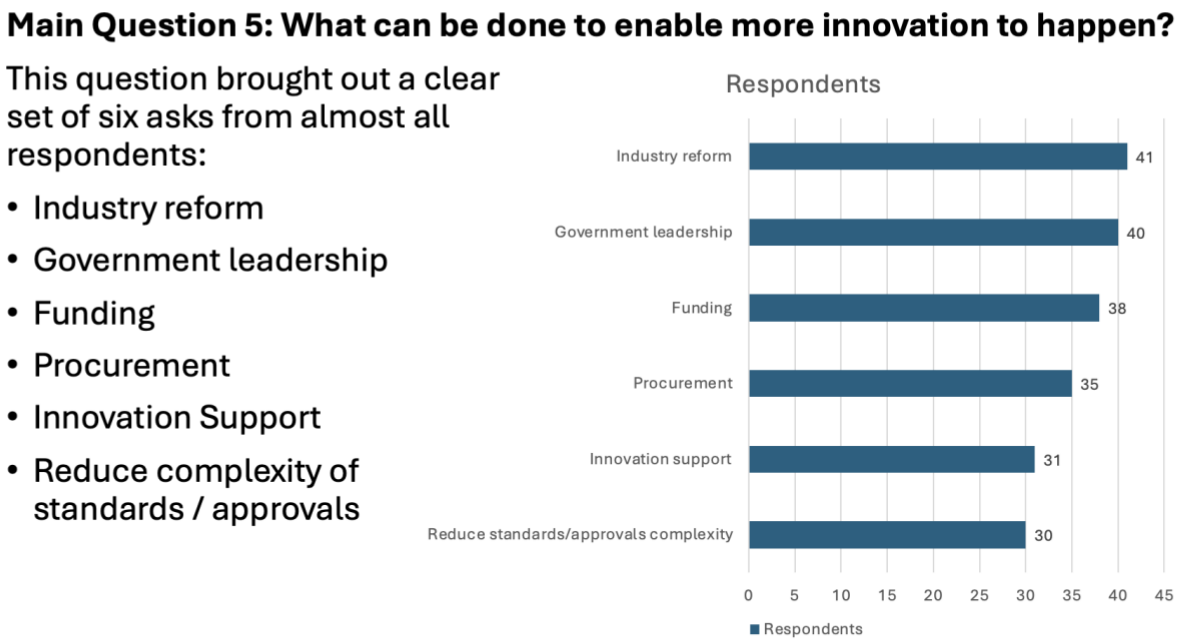

Figure 6.10: Overview of responses to Main Question 5

These figures provide a broad overview of the data collected from the 43 interviews undertaken for this research. However, it is important to remember that the purpose of the interviews was to collect qualitative data, which will be analysed and discussed in the next section.

6.4.3 Thematic overview of the data

To assess the qualitative data collected from the interviews, a number of themes have been drawn out from the interviews. Nine key themes have emerged:

(1) The role and purpose of innovation in rail
(2) The ability to innovate and openness to innovation
(3) Industry structure and fragmentation
(4) The culture of the rail industry
(5) Risk appetite and costs of / benefits from innovation

(6) The availability of funding
(7) The availability of skills
(8) The availability of support and facilities
(9) The role of government and client bodies

These themes will be assessed against all the other data collected later in this chapter. In this section, the themes will be more fully explained and analysed using the data from the interviews.

The role and purpose of innovation in rail

The first theme is the role and purpose of innovation in rail. All the forty-three interviewees addressed both supply-side considerations and demand-side considerations. For the former, this was expressed as exploiting new technologies (particularly in the fields of digitalisation and decarbonisation) to provide improvements to railway operations in many ways. From a demand-side perspective, the role of innovation as a means of addressing major industry challenges was almost universally cited. A clear and universal focus was on how innovation is needed to support the railway to provide better, more reliable services, and to improve value for public money by reducing costs.

One interviewee from the supply industry explained their perspective in this way,

"*We can provide much better solutions, the advances in digital technologies, in particular, allow for transformational improvements in processes and services. It's now up to the industry to take advantage of this*!" (from Group 'SI')

Another supply industry interviewee connected improved services with the macro-benefits of making improvements to the railway in terms of driving wider environmental, social, and economic benefits,

"Innovation brings efficiency and reduced costs and supports big objectives like climate change as well as driving other economic and social benefits." (from Group 'SI')

Correspondingly, an interviewee from the operations side put it as,

"*The industry is in the doghouse with the Government, we have got to deliver serious improvements to services while spending less money. That means we must do things* *differently. So, we need to make use of innovation to deliver those changes rapidly*." (Group 'OP')

The ability to innovate and openness to innovation

The second theme covers both the ability to innovate and openness to innovation. This broad theme considered both supply-side issues - including the lack of incentives to innovate (for example, procurements being focused on specification of known and proven technology, thereby blocking opportunities for innovative solutions) – and demand-side issues (for example, a fear of the unknown and a lack of risk appetite to try new and better solutions against known and existing solutions). This theme frequently came out as a part of the issue with industry culture, with a majority of interviewees across all three groups referencing an equivalent phenomenon, described as "*railway treacle*", "*stagnancy*", "*inertia*", and "*paralysis*", one railway key actor explained it as,

"The UK has a strange relationship with the railways as we invented it, like football, and yet everyone else has gone off with it and made it better and we are left behind. The UK railway panics about having to actually do innovation as it tries to balance being a part of the nation's industrial heritage, part of the current economy, and part of the future society." (from Group 'ST')

In addition to the phenomenon of 'railway treacle', a more sceptical view was also prevalent that viewed innovation as a tool for the railway industry to deliver "*positive messaging and improved communications*!" (from Group 'ST').

One example was cited from the German railway,

"*Innovation sometimes happens to show paymasters that they are modern and effective – for example, a few years ago Deutsche Bahn set up the Mindbox in Berlin with a very strong start up culture and purposefully designed to be as far removed from the railway industry as possible – this led to some successes commercially but there was a clear purpose to it of demonstrating that the railway can be modern and innovative*!" (from Group 'ST').

Industry structure and fragmentation

The third theme can be summed up as industry structure and fragmentation. This was the major issue and was mentioned by every interviewee repeatedly. The lack of coordination and, at a higher level, the lack of a long-term strategy and vision for the role and purpose of the railway, was universally cited as a critical barrier to innovation. Time and again the lack of joined-up thinking and approach was referenced, with much hope expressed that forthcoming reforms would address this – albeit the hope was tempered by a lack of confidence in it being delivered by several interviewees.

An underlying theme was the lack of a focal point for innovation. Many interviewees raised a lack of industry leadership in providing a demand for innovation as a key problem and six interviewees specivically referenced the loss of the British Railways Research Department as a root cause of that. One issue raised several times was the difficulty in approaching the railway with unsolicited ideas and bids for innovation projects. There is no easy route to enter the railway market with novel solutions, combined with the complexity of getting the requisite testing and approvals, making validation and adoption of innovations difficult.

One interviewee summed this specific problem up as,

"*The UK railway needs a champion to push new ideas and an openness to innovation, an enabler who can unlock not just projects but, ultimately, mindsets*." (from Group 'SI')

The culture of the rail industry

The fourth theme is the culture of the rail industry. This was raised by the rail supply industry interviewees frequently as a lack of desire to try new solutions or new technologies, with the operating railway instead preferring known and understood solutions that were less risky to procure and deploy. Several interviewees in Groups 'SI' and 'ST' expressed concern over the lack of tangible, visible leadership in supporting innovation in rail from the demand side, for example one interviewee stated,

"*It is easy to talk about how the railway welcomes innovation, but we simply do not see it happening on the ground*."

Another interviewee connected this theme with the second theme about openness to innovation, "*It is hard to follow where the industry-leading innovation really is compared to all the chatter about what looks good*." (from Group 'ST')

A number of comments from interviewees summarise the problems that emerged around the theme of industry culture:

"*Why don't people understand that the railway is simple and therefore innovation should be easy – railway starts with the complete opposite perspective of complexity*?!" (from Group 'SI')

"*We need to get over the arrogance of the rail industry that it – and only it - knows best about running a railway*." (from Group 'SI')

"*Innovation fails on the railway because we never get to even proving concepts*." (from Group 'SI')

"*Companies are finding that relationships are fraught, contractual complexity is the overriding theme for the railway, the railway always makes everything hard for itself and absolutely no one is brimming with optimism*." (from Group 'SI')

"*The optics are very clear for us - do what you have to do for less - which is a barrier to innovation*." (from Group 'OP')

"*The Department for Transport don't like anything different; their sole focus is on cost control to appease the Treasury; they have no money and so no innovation can really be driven forwards*." (from Group 'OP')

"*The culture is engrained into the industry – we don't make it easy to try things – the balkanisation of the industry after privatisation has entrenched behaviours that baked in cost and risk aversion and an immutable focus on safety at any cost after the big accidents around the turn of the millennium*." (from Group 'ST')

"*The UK rail industry needs to take a sober look at itself – does it really help good ideas get through the permafrost of the industry? I can give a couple of good examples… but why are there not dozens of SMEs breaking through, given the size of the industry and the role of the railway there should surely be many more*?" (from Group 'ST')

"*The industry is characterised by contractual interfaces at every turn and conservatism when it comes to trying new things, and it is also so defensive – this makes it hard to criticise and* *that rarely happens because this industry is defined by its personal relationships and sticking with who and what you know*!" (from Group 'ST')

Risk appetite and costs of / benefits from innovation

The fifth theme is risk appetite and the costs of, and corresponding benefits from, innovation. Interviewees observed that the cost of innovation does not necessarily correspond with where the benefits are derived. This is part of the structural complexity of the rail industry as one interviewee explained in a practical example,

"Train Operating Companies want to spend as little as possible so look to Network Rail to deliver electrification, which will significantly reduce the cost of operations and provide wider benefits for passengers." (from Group 'OP')

The buyers of innovation don't want to bear significant risk, but the cost of innovation to get new products and solutions approved and commercialised is significant, creating a massive barrier for innovation.

One interviewee provided a forecast,

"*This will be a defining challenge for the next 10 years, the pros and cons for technology introduction across the track-train divide, such moving signalling from trackside to trainborne. How will this get paid for*?" (from Group 'ST')

The availability of funding

The sixth theme is the availability of funding. There is not a lot of investment to support UK railway innovation, and this has been impacted by Brexit, as one interviewee from Group 'SI' explained,

"The impact of Brexit was horrendous as our main source of funding for rail research, development, and innovation, disappeared. Now we have regained access to EU Horizon funding and the Europe's Rail Joint Undertaking, we are all making a huge effort to rebuild those collaborations and try to regain those funding opportunities."

With relatively little public funding available to support rail innovation, building the business case to deploy private investment is difficult. As one interviewee from Group 'SI' explained,

"To get private investment, innovation needs to be proved, and the practical application demonstrated to unlock that investment. The rail industry needs to take the lead in showing the potential application of these innovations. And remember that rail is competing with many other sectors for investment!"

Another interviewee from Group 'SI' stated,

"*We are told that there is funding to support rail innovation, but it never seems to materialise. Innovation is expensive in rail… if there is little funding support then there will be very little innovation*!".

A specific issue with how the limited funding was allocated was raised several times by interviewees from Group 'SI' and 'ST', summarised by one as,

"Innovate UK are the main providers of funding to support rail innovation, but it is allocated in a haphazard way. Scoring seems to be done by people from outside the industry with little practical knowledge or experience. Many people don't bother wasting time bidding given the uncertainty that you will be fairly or rationally assessed and scored!" (from Group 'SI')

One further interviewee summarised the context and looked to find potential solutions,

"*The leaders at the Department for Transport and Network Rail have the power to demand innovation and to provide the funding to make it happen. Why can't Network Rail go to a small company and try out potential solutions using small grants to seed developments? Why not connect funding for innovation with opportunities for skills development? The barrier is money, but it is also short-term thinking and not wanting to actually try and solve the problem*." (from Group 'ST')

In the majority of interviews, funding came up as a critical and tangible barrier to innovation, following the culture of the industry and the role of Government and industry structure.

The availability of skills

The seventh theme is the availability of skills. Generally, interviewees were confident that the skills to undertake rail innovation exist, although there were some concerns about ensuring that access to the next generation of railway engineers continued due to concerns over other industries being more attractive.

However, there was greater concern among interviewees that the skills to implement new technologies and to understand and support them higher up the chain are lacking. This part of the theme corresponds with points made around industry culture and openness to innovation.

"*The industry needs to be able to accept challenges as to why rail does certain things in certain ways and actually start to challenge itself rather than just saying it will do so*." (from Group 'SI')

The availability of support and facilities

The eighth theme focuses on the availability of support and facilities needed to enable innovation. To sum up the views of the majority of interviewees, some support does exist but there is not much. Additionally, access to facilities to support the development, testing and validation of innovations is limited and expensive. A number of interviewees considered this a major barrier with innovation support limited to a few organisations and sites.

Fifteen interviewees cited the importance of universities, including the UK Rail Research and Innovation Network (UKRRIN), as having a role to play in supporting innovation, although one interviewee stated,

"*UKRRIN and the University of Birmingham in particular have been major players in supporting rail innovation although even this seems to be falling away as the money has dried up*." (from Group 'ST')

The Global Centre of Rail Excellence (GCRE), currently in development in South Wales, was cited by six interviewees as a facility that is desperately needed and should be supported to facilitate more innovation for the UK railway. On this subject, one interviewee observed, "*The GCRE is a megaproject and yet we hardly hear politicians in Westminster even talking about it. Do they actually support it*?" (from Group 'ST')

The role of government and client bodies

This leads into the ninth and final theme which is the role of the government and client bodies (these are the public bodies with the buying power to deliver the railway outside of the Department for Transport, such as Network Rail, High Speed 2, East West Rail, and Transport for London).

Every interviewee raised this as a key issue for the UK railway innovation landscape. The consensus view was clear – the government should play a visible leading role in encouraging and supporting rail innovation. This should go beyond words and should take the form of specific actions, including (but not limited to) funding, as well as using policy instruments to reduce the barriers put up by procurement and regulations to innovation.

Interviewees comments included:

"*The railway is in a long-term reform process, but innovation has barely registered in any substantive measure*." (from Group 'SI')

"*Innovation is always asked for but never actually supported*." (from Group 'SI')

"*It (innovation) always seems to be a gimmick or an add-on, never really a fundamental that is structured into the actual delivery process*." (from Group 'OP')

"We want to focus on buying and seeking innovations to answer tangible problems right now, but we don't have the ability to do that because of the current government control." (from Group 'OP')

"*The demand side could drive innovation, but they won't step up to the plate for whatever reason*." (from Group 'ST')

"*Institutional inertia is a massive issue. The Government and its bodies including Network Rail and GBR have got to step up to the plate at some point*." (from Group 'ST')

6.4.4 Review of the findings

Overall, the interviews provided a much richer volume of data to support a descriptive analysis of the UK railway innovation landscape. The nine themes identified from the qualitative data collection are helpful in enabling the research to focus, and to integrate the source of data more effectively.

Three overarching themes came out as being of clearly more significance in acting as barriers to the UK railway innovation landscape: (1) the culture of the industry, (2) funding, and (3) the role of the Government (including the structure and fragmentation of the industry).

6.5 Integration of quantitative and qualitative data and analysis

In this section, the quantitative and qualitative data is integrated and analysed, as per the concurrent transformative mixed methods research design (discussed in chapter 3.2.5).

The primary quantitative data was collected via an online survey with 202 responses, while the primary qualitative data was collected via in-person interviews with 43 railway professionals.

The quantitative data provided a stark picture of the UK railway innovation landscape. The general perspective of the UK railway is that it is not very innovative, and certainly less innovative than its counterparts overseas, and then the automotive and aerospace industries. The UK railway is seeing innovation across several subject areas, with digitalisation and decarbonisation standing out as the two largest areas of opportunity currently and likely to have the biggest impact over the next decade.

Key factors in driving innovation (i.e. potential enablers from a supply-side perspective) were ranked as funding, then innovation support, then Government policy and regulation, followed by technological advances and market demand. While barriers to innovation were ranked as resistance to change (industry culture), fragmentation (industry structure), and political uncertainty and lack of support, then followed by costs and procurement processes.

Respondents highlighted industry culture and government leadership as very clearly the two most effective ways of accelerating UK railway innovation, with industry structure and funding raised as the third and fourth most important factors.

The qualitative data collection provided an opportunity to probe interviewees for a richer picture of the UK railway innovation landscape.

The interviewees were unanimous that the railway needs to use innovation to improve services and reduce operating costs. Additionally, the competition from other modes of transport and the opportunity to exploit new technologies were also identified as key reasons to innovate.

Interviewees also gave a pessimistic perspective on the current UK railway innovation landscape, with the fragmentation of the industry (i.e. industry structure), the lack of funding, and a lack of Government support, being key reasons for a clear majority having a negative perception.

The key actors in the UK railway innovation landscape were identified as the Government, Network Rail, and other client bodies – the key economic buyers of railway innovation supply; with rail operating companies, original equipment manufacturers, and small and medium-sized enterprises all featuring frequently.

When the discussion moved to enablers and barriers to railway innovation, the top four factors were: industry structure, industry culture, the role of government, and funding. Interviewees were consistent in their views on how to enable more innovation to successfully happen – industry reform, leadership from the Government, availability of funding, changes to procurement processes, more innovation support (with facilities and funding to support development, testing and validation), and reducing the complexity of the standards and the time and cost of obtaining product approvals to be able to enter the market more easily.

From the interviews, nine recurring themes emerged:

(1) The role and purpose of innovation in rail
(2) The ability to innovate and openness to innovation
(3) Industry structure and fragmentation
(4) The culture of the rail industry
(5) Risk appetite and costs of / benefits from innovation
(6) The availability of funding
(7) The availability of skills

(8) The availability of support and facilities

(9) The role of government and client bodies

These themes all correspond with outputs from the quantitative data collected, as illustrated in figure 6.11.

Nine themes from qualitative data	Correspondence with quantitative data
The role and purpose of innovation in rail	• The need for innovation to reduce costs and improve services; rail should play a leading role in addressing environmental and sustainability challenges through innovation (q.12)
The ability to innovate and openness to innovation	• Resistance to change being the biggest barrier to innovation (q.9) and industry culture being the most important factor to address in accelerating rail innovation (q.15)
Industry structure and fragmentation	• Fragmentation/industry structure being the second biggest barrier to innovation (q.9) and the third most important factor to address in accelerating rail innovation (q.15)
The culture of the rail industry	• The UK railway is not considered very innovative (q.1) and industry culture being the most important factor to address in accelerating rail innovation (q.15)
Risk appetite and costs of / benefits from innovation	• A number of both supply-side and demand-side factors, including industry culture and structure, procurement processes, barriers to entry caused by standards and approvals processes/requirements
The availability of funding	• Availability of funding being the most important factor in driving railway innovation (q.8) and fourth most important factor to address in accelerating rail innovation (q.15)
The availability of skills	• Cited several times in free text answers (q's .9, 12,15)
The availability of support and facilities	• Access to innovation support being the second most important factor in driving railway innovation (q.8) and the fifth most important factor to address in accelerating rail innovation (q.15)
The role of government and client bodies	(1)The third most important factor in driving railway innovation (q.8), the third biggest barrier to innovation (q.9), and the second most important factor to address in accelerating rail innovation (q.15)

Figure 6.11: Chart illustrating correspondence between themes identified in qualitative data collection and the quantitative data collected

The outputs and themes from the quantitative and qualitative data will next be used to inform the case studies and are then integrated with the secondary data (the PESTLE analysis, the analysis of internal factors, and the case studies) to undertake a detailed critical analysis.

6.6 Chapter Summary

In this chapter the qualitative data that was collected has been set out and analysed; this has then been integrated with the quantitative data collected to synthesise the two key sources of primary data for this research. From the analysis of the primary data, nine key themes have emerged (figure 6.12).

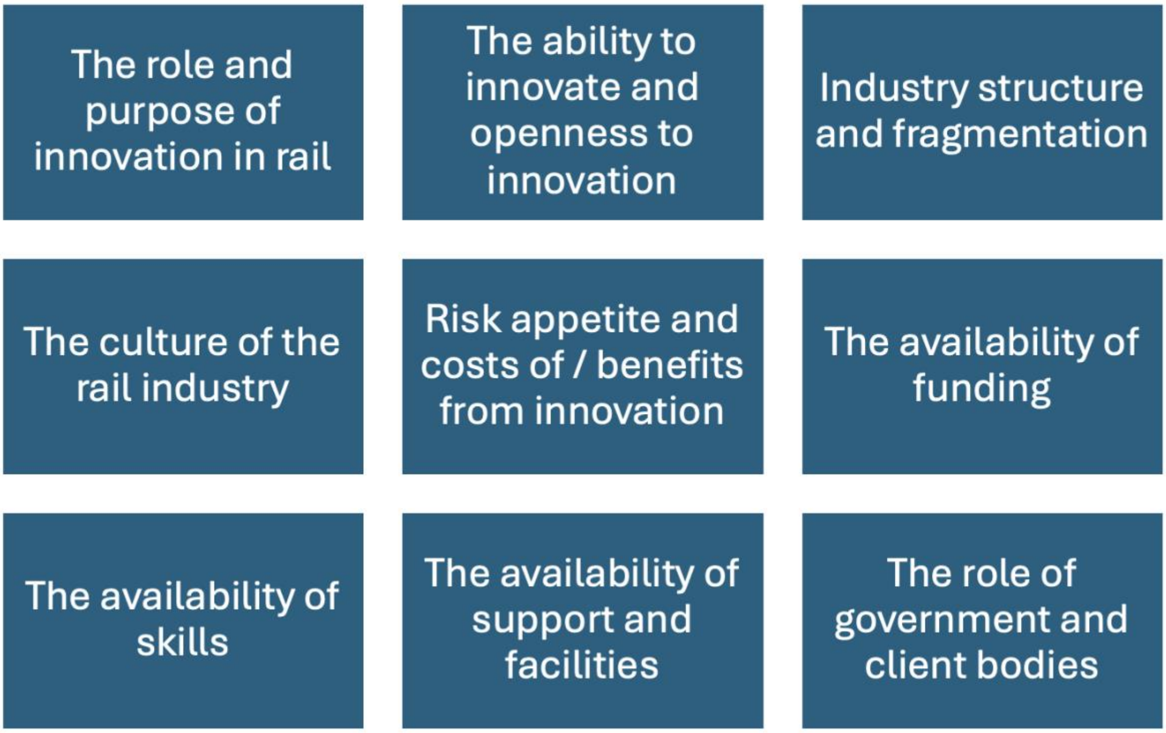

Figure 6.12: Nine key themes influencing UK railway innovation identified from the primary data

Figure 6.11 (see above) summarises the correspondence between the nine themes identified across the qualitative and quantitative data. In the next chapter, the research will use case studies to collect further relevant data about railway innovation.

Chapter 7: Observation and Analysis (Case Studies)

Chapter Structure

7.1 Introduction

In this section, the research investigates several railway innovation projects, from both the UK and mainland Europe, in the field of sustainable railway traction power systems. These case studies are used to investigate and analyse the evidence and to inform the development of the conceptual framework in the next chapter.

The topic of sustainable railway traction power systems is fruitful in the railway innovation landscape, as an area that has received much attention over the last decade. With environmental and sustainability awareness and concerns having significantly increased, all modes of transport need to address decarbonisation to support the Government's long-term decarbonisation requirements (for example, Transport Decarbonisation Plan, Department for Transport 2021).

The field of sustainable railway traction power systems concerns the source of the tractive power that is used to propel trains. At present, 39% of the UK railway infrastructure is electrified (6130km out of a total of 15849km, Office of Rail and Road 2024) – it has overhead line equipment that provides electrical energy directly to electric trains. That means that the majority of the UK railway route network is unelectrified and requires trains to move under their own power – usually using diesel traction power that burns fossil fuel and produces carbon and particulate emissions.

Traction emissions are the predominant source of greenhouse gas emissions generated by the UK railway. For example, the UK train operating company, West Midlands Trains, runs a mixed fleet of electric and diesel trains serving the West Midlands region, and traction energy accounts for 94% of their scope 1 and 2 carbon footprint (ie directly incurred by WMT operations, not including supplier activities) (West Midlands Trains 2023).

As identified in the primary quantitative data collected from the Survey, the responses to three of the questions highlight the significance of the subject of decarbonisation and its importance within the UK railway innovation landscape:

- In Question 7, 52% of the respondents considered decarbonisation to be one of the areas undergoing the most innovation in the railway industry – the second highest area, after digitalisation/data.

- In Question 10, 24% of respondents (the second highest grouping) identified decarbonisation as likely to be the area of railway innovation that will have the most significant impact over the next ten years.
- In Question 12, the majority of responses (56%) stated that the railway already does, or should be, playing a leadership role in using innovation to address environmental and sustainability challenges. A significant proportion of responses specifically mentioned sustainable railway traction systems as an area that the railway should be focussing innovation efforts upon.

In the primary qualitative data collected from the key actor interviews, climate change was identified as the fifth key reason for the railway needing innovation. Interviewees frequently cited the need for decarbonisation, and the opportunity for the railway to showcase its credentials as a sustainable form of transport.

The author's primary experience in railway industry innovation in the field of decarbonisation make this a relevant topic to investigate further and to provide the case studies for this research.

7.2 UK Railway Innovation Projects

Railway traction power systems have been a longstanding subject matter for innovation. From the invention of the steam engine and its application to railway transport, followed by the deployment of electrical systems (the UK Southern Railway) and diesel traction (Vickers 1999).

Using the Multi-Level Perspective framework, the railway is a socio-technical regime with a set of established social and technological norms that are well-known and understood. In the context of traction power systems, that is currently electric traction (using either the 25kV AC overhead line equipment or the third rail 750v DC system) to power the traction motors, or else power from diesel combustion engines utilising either electric motors or hydraulic systems to propel trains.

However, the wider landscape has evolved due to the megatrend of climate change which has shifted political and social perspectives towards demanding decarbonisation. This has created opportunity for research and innovation in the field of railway traction systems to investigate the niche of novel sustainable traction power – such as hydrogen and battery technologies – to provide zero emission alternatives to diesel.

This niche could trigger the technological transition away from diesel (bottom-up approach) or Government policy could drive the established technological norms of the regime away from diesel towards these alternatives from the niche (top-down approach) - figure 7.1 illustrates this.

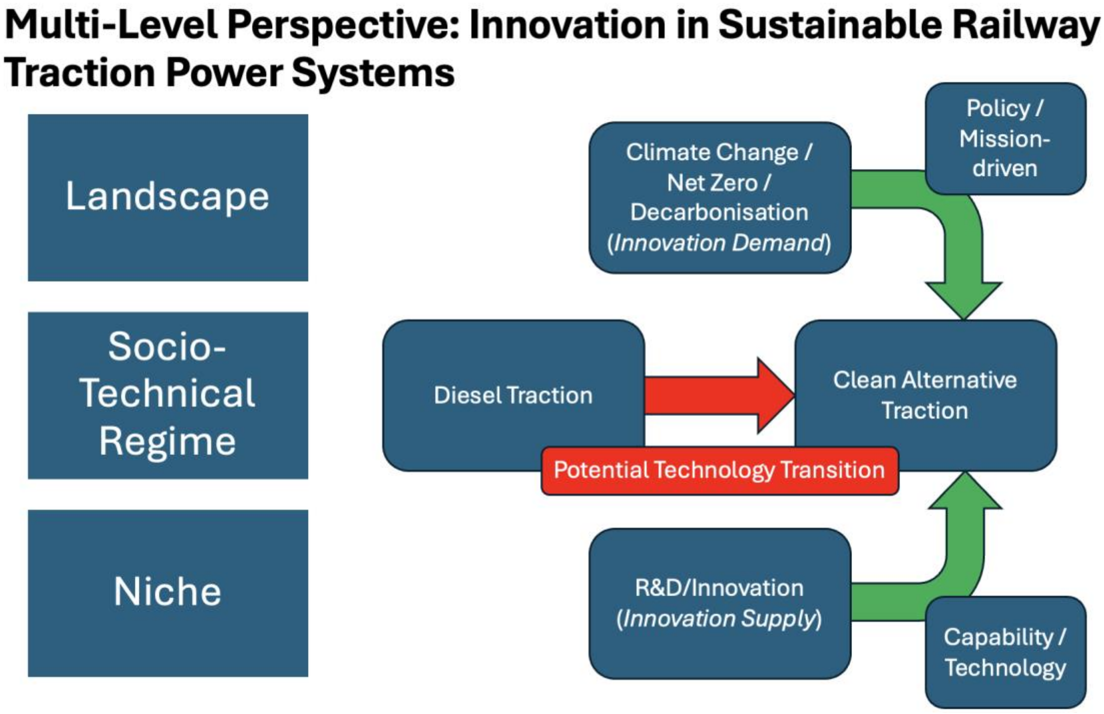

Figure 7.1: Illustration of the innovation model of the multi-level perspective, applied to the topic of sustainable railway traction systems

The motivation to develop and implement innovation can come from either of these approaches:

- Top-down approach: from the demand side, specific problems seeking solutions.
- Bottom-up approach: from the supply side, solutions designed to address identified problems.

Using the social construction of technology's theoretical approach, these case studies will investigate the development of these innovation case studies within their wider network of actors and institutions. This network of actors and institutions feeds into the multi-level perspective analysis across all three levels:

- At the landscape level, the demand side can identify the problem and potential solutions and put pressure on the regime to find and deploy solutions. Using the social construction approach, the innovation network will inform and engage at this level to generate sufficient knowledge and awareness to start applying that pressure.
- At the regime level, the established state of the art will be defended. The innovation network may consider a conciliatory approach or a promotional approach, however the role of the landscape is crucial in opening the space for an innovation to create a technological transition.
- At the niche level, the innovation network is crucial in developing the innovation not just as a technological sound solution, but as a feasible, practical, and commercially viable alternative to the socio-technical regime's established and preferred state of the art.

The theories of multi-level perspective and social construction of technology provide a coherent and consistent method for analysis which will be used alongside the other models of innovation investigated earlier in the research.

This part of the research will investigate case studies from the UK and European railway innovation landscapes over the last fifteen years to inform the analysis.

7.2.1 The Independently Powered Electric Multiple Unit (IPEMU) project

The IPEMU project saw a 4-car Class 379 electric multiple unit retrofitted with additional traction batteries to create a hybrid drive system that could operate as a regular electric train using the overhead line equipment, or else operate on unelectrified routes using the battery traction power system.

Figure 7.2: The IPEMU train on test, photo from Network Rail

The project started in 2013 and culminated in the prototype unit going on trial in early 2015 in the East of England for five weeks to obtain data from a real-world rail operating environment.

The objective of the project was to better understand the technological potential for using battery technology to provide power for short routes (of up to 30km) to accelerate the phasing out of diesel and avoid the procurement of new diesel train fleets.

The project was funded by Network Rail, the Department for Transport, the Railway Safety and Standards Board, and was supported by Bombardier (the train manufacturer), and Greater Anglia (the train operator).

Of particular interest to this research is the role of the actors in making the innovation project happen. The asymmetry between where the cost and risk lay in such a project compared to where the potential benefits would sit were apparent (Rail Engineer 2015). The key to the project was the ability to form a collaborative partnership with the motivation to tackle the challenges for the greater long-term good of the industry.

As one of the partners said at the time,
"*It is a great example of cross-industry collaboration. The cost of a demonstrator was not feasible - it needed partnership, and that is what we got.*

This idea came from the Rail Technical Strategy, and there are opportunities to look at parts of the network that are not electrified." (Clinnick 2015)

This project demonstrates open innovation in action with multiple partners working together collaboratively. It is also an example of strategic niche management (Rip & Kemp 1998) where key actors collaborate to facilitate the strategic development of technology that they know is going to be needed in future application.

7.2.2 Chiltern Railways – Hybrid Drives

In 2022 Chiltern Railways, one of the UK train operating companies, operating out of London Marylebone with a 100% diesel fleet, trialled two versions of a hybrid battery-diesel drive technology with two separate rolling stock owning companies (ROSCOs).

The Hydrive project saw a Class 165 suburban diesel multiple unit, owned by Angel Trains (the first ROSCO), being retrofitted with a Magtec hybrid drive to provide battery traction power to the unit to cut diesel emissions and engine noise in and around stations.

The HybridFLEX project saw a Class 168 mainline diesel multiple unit, owned by Porterbrook (the second ROSCO), being retrofitted with a MTU hybrid drive to allow the diesel unit to run on battery power in and around stations, increased fuel efficiency by up to 25% while also reducing CO_2 and particulate emissions and noise. The unit was launched in 2022 (Chiltern Railways 2022) but was withdrawn the following year.

Figure 7.3: The HybridFLEX class 168

In mid-2023 Chiltern Railways confirmed that both hybrid drive trial units had been withdrawn, with the train operator citing the cost of deploying the technology making it unviable (Railway Business UK 2023; Hunt, London Evening Standard, 8 Sept 2023).

This case study demonstrates Rothwell's fourth generation of innovation process, with the suppliers (Angel and Porterbrook) integrating with the train operating company in the innovation process to undertake the development and testing activities.

7.2.3 Chiltern Railways – Hydrotreated Vegetable Oil

In 2023, Chiltern Railways launched the use of hydrotreated vegetable oil (HVO) as a fuel to power its five mainline diesel locomotives. HVO is an alternative to diesel and is produced from cooking oil, tallow, and other recyclable wastes, instead of being a fossil fuel. HVO also burns more cleanly, producing fewer greenhouse gas emissions and air particulates (claimed reductions of up to 90% and 85% respectively, Chiltern Railways press release 27 July 2023).

Figure 7.4: Chiltern Railways Class 68 locomotive, powered by HVO

This innovation was the result of significant innovation demand from Chiltern Railways, as the only train operator running a completely diesel-powered fleet of trains from a Central London terminus station (Lydall, London Evening Standard, July 2023).

Equally, this clearly illustrates an example of the pressure from the socio-technical landscape onto the railway as a socio-technical regime to undertake a technological transition – remove diesel railway traction power from a large mainline station in the centre of the UK's capital city.

7.2.4 HydroFLEX

In 2018, the Birmingham Centre for Railway Research and Education (BCRRE) partnered with Porterbrook to scale up its traction system technology to develop a prototype demonstrator that would be the UK's first hydrogen-powered train (University of Birmingham 2018). The project was motivated by the political context, with the UK government highlighting the importance of tackling climate change – the role of legislation and standards in signalling the demand for this technology to be developed was a key factor (Calvert et al 2021). The technology had also been shown to be sufficiently mature from the Alstom project in Germany (Calvert et al 2021) – this European case study is discussed below.

Nine months later, the full-size 'HydroFLEX' prototype demonstration unit was successfully launched at a major industry event, showcasing the potential for this new technology to support rail decarbonisation – which at the time, was a major political priority for rail policy (BBC 2019, UKRRIN 2019, Hirschlag 2020).

Figure 7.5: The HydroFLEX project team, 2019

Following two successful bids for innovation funding from the Innovate UK First Of A Kind competitions in 2019 and 2020 (UK Research & Innovation 2020, UKRRIN 17 June 2020), the project team were able to use the £750,000 from the two Innovate UK grants, along with matched investment from the partners, to develop the second HydroFLEX demonstrator unit which obtained mainline approval to operate in 2020, making it the UK's first mainline hydrogen train.

Figure 7.6: HydroFLEX prototype demonstrator on mainline testing at Evesham, 2020

The unit's innovative technology was showcased at the United Nations COP26 climate change conference in Glasgow in November 2021 (Green Business Journal 2021, Modern Railways 2021, Energy News Biz 2021).

Since its showcase at the COP26 conference, the unit has undergone significant development, testing, and proving. In addition, Porterbrook have been seeking market opportunities for the unit to go on trial in a commercial operating environment.

This project can illustrate aspects of several innovation theories in application:

- 5th Generation of Innovation Process: the partners established an integrated project team with key suppliers and built an effective collaborative network to push the project forwards.
- Open Innovation: the initial partnership quickly focused on establishing a collaborative joint team approach with the supply chain. Key to this was an understanding of needing a system approach to focus on the outcome while working through all of the technical challenges within the development process.
- Mission-Oriented Innovation: the partnership was established in response to the UK government's challenge to the rail industry to develop technological solutions to decarbonise railway traction systems.

- Multi-Level Perspective: the roles of the landscape, the socio-technical regime, and the niche can all be illustrated by this project:
    - Landscape: the UK government had set legal targets and a clear ambition to decarbonise the railway, sending a statement to the socio-technical regime that this issue needed addressing.
    - Socio-technical regime: very comfortable talking about a long-standing process of electrifying the railway network infrastructure, but from a purely technical perspective without consideration of the political and economic factors.
    - Niche: the innovation project of demonstrating the feasibility of retrofitting hydrogen/battery traction onto an existing train.
- Neo-Schumpeterian theories of innovation:
    - the role of actors and institutions beyond the partners were instrumental in enabling the project. The innovation system model was key with actors and institutions including the regulator (ORR), the standards body (RSSB), the infrastructure manager (Network Rail), the national innovation funding agency (Innovate UK), and politicians (including the then Secretaries of State for Transport at the time of the project – Chris Grayling and Grant Shapps), all playing a part in the eventual success of the project.
    - the theory of evolutionary growth can also be applied. The research underpinning this major innovation project had been started fifteen years previously and was well-understood (Hillmansen 2003). As such, this had been a long process to demonstration rather than a radical innovation from out of nowhere.
- Social Construction of Technology: one critical aspect in this project was the role of the network of actors and institutions in taking this project forwards successfully. The work to obtain political and economic support to enable the project to proceed as far and as quickly as it did was due to a wide range of support from actors and institutions both within and without the collaborative project team.

The research will return to the HydroFLEX project in more detail in Chapter 10, as this project will be used as a full case study later in the research.

7.2.5 HydroShunter

Following the development of the HydroFLEX project, the project team from the University of Birmingham established a spin out company to further develop and commercialise the technology (Crampton 2024). This spin out company established a partnership with the Severn Valley Railway, a leading heritage railway, and private investment to fund the retrofit of a Class 08 diesel shunter locomotive with the hybrid hydrogen/battery technology to showcase its application in a railway locomotive. (BBC News 2021, Vanguard 2024).

Figure 7.7: HydroShunter in development at the Severn Valley Railway, provided by Vanguard Sustainable Transport Solutions Limited, 2024

The HydroShunter locomotive project uses the modern technology of hybrid hydrogen/battery traction retrofitted into a 70-year-old shunter locomotive to demonstrate the practical application and opportunity for the technology to be used to decarbonise railway operations.

Returning to our theoretical models, this project illustrates several models of innovation in application including:

- Open Innovation: the project was built from an initial collaborative partnership between Vanguard and the Severn Valley Railway, to also include the University of Birmingham and other suppliers (Crampton 2024).

- Mission-Oriented Innovation: the clear intent of the project was to provide a practical demonstration of how this technology can be rapidly implemented to decarbonise railway operations.
- Innovation Systems: the partnership built wider support from actors including the Clean Futures Accelerator and the Black Country Innovative Manufacturing Organisation to support the development programme.

The research will return to the HydroShunter project in more detail in Chapter 6, as this project will be used as a second full case study later in the research.

7.3 European Railway Innovation Projects

In mainland Europe, similar challenges are also being addressed by the railway industry. The challenge to decarbonise railway operations is identical and has generated demand for innovation.

7.3.1 Alstom Coradia iLint

In 2016, the global railway rolling stock and systems manufacturer Alstom unveiled the world's first hydrogen-powered train, the Coradia iLint (Alstom 2016). The unit was a variation on the existing Coradia Lint regional multiple unit design, with the diesel engines and fuel tanks replaced with hydrogen fuel cells and hydrogen storage.

Figure 7.8: Alstom Coradia iLint, taken from Alstom website

Unlike the HydroFLEX project in the UK, Alstom had signed Letters of Intent with four German regional authorities for the development and supply of a zero-emission multiple unit to replace existing diesel fleets (Alstom 2016).

This development of the world's first hydrogen train fits with Rothwell's 4th generation of innovation process, with Alstom developing an integrated supply chain to develop and deliver the innovative new product to market. There is also a clear fit with the neo-Schumpeterian theory of innovation systems with the role of multiple actors and institutions – notably the German regional authorities as early customers - key to enabling the project to happen.

7.3.2 FCH2Rail – an EU-funded hydrogen rail application

The FCH2Rail project was funded by the Clean Hydrogen Partnership – a European Union Joint Undertaking - to develop a bi-modal (hybrid electric/hydrogen) multiple unit, using a CAF-manufactured electric multiple unit as the base vehicle to develop. The project consortium, led by the Spanish train manufacturer CAF, brought together partners from Belgium, Germany, Spain and Portugal (FCH2Rail 2024).

Figure 7.9: FCH2Rail demonstrator train, taken from the FCH2Rail website, credit CAF

The Clean Hydrogen Partnership is a Joint Undertaking - an entity established by Article 187 of the Treaty of the Functioning of the European Union to aid research, development, and innovation projects in the EU. Joint Undertakings are public-private partnerships between the EU, industry associations, companies, and other relevant organisations, established to drive the industrial research agenda in their sector areas (EUR-Lex). The Council of the European Union approved the establishment of nine Joint Undertakings, including the Clean Hydrogen Partnership, in 2021 (Council of the EU 2021).

The objective of the Clean Hydrogen Partnership is to support the development of the EU hydrogen economy, by accelerating the development of hydrogen technologies, to support the long-term decarbonisation of the EU energy system as well as strengthening the competitiveness of the EU in hydrogen technologies (Clean Hydrogen Partnership 2024).

The FCH2Rail project is a clear example of mission-oriented innovation policy in application. With EU funding providing the incentive and support to enable the establishment of a multi-national collaborative partnership of actors from the railway innovation landscape. The partnership can be characterised as an open innovation partnership, bringing together knowledge and expertise from multiple organisations to undertake the development process. Additionally, the key role of an innovation network of actors collaborating to drive forward the technological development from a supply-side perspective, in partnership with and directly supported by actors from the demand-side, demonstrate the importance of the innovation system and the importance of actors and institutions.

7.3.3 Battery Electric trains from Koncar

Croatian rolling stock manufacturer, Koncar, launched their battery-electric and battery multiple units at the Innotrans international trade fair in Berlin in September 2024. These products were developed in response to market demand for electrified public transport solutions; and, as with the Alstom Coradia iLint, that market demand was already committed with HZ Passenger Transport (the Croatian national passenger rail operator) having committed to procuring a first production unit of each vehicle in 2022 (Koncar 2022).

Figure 7.10: Koncar Battery Electric Multiple Unit at Innotrans 2024

The development of these units has been undertaken by Koncar with its suppliers in what can be characterised as Rothwell's 4th generation of innovation process, with an integrated development process for the technology and its design for railway application.

As with the Alstom Coradia iLint example, the role of the innovation system has been important in providing an established demand side for the innovation to respond to. Using the social constructivist theory, the battery trains project by Koncar has built up a successful system that brings together the Croatian government, the Croatian passenger railway operator (HZPP), and Koncar and their suppliers, to develop an innovative new product (the innovation supply) to answer the specific innovation demand for battery technology to be introduced onto the Croatian railway.

7.4 Chapter Summary

In this chapter, several case studies from the UK and the European Union in the field of sustainable railway traction power systems have been identified and analysed. Learnings from the models of innovation identified in chapter 2 have been applied to support this analysis. In the next chapter, all the data observed and collected is synthesised and critically analysed to inform the research and to develop a model of the UK railway innovation landscape.

Chapter 8: Synthesis and Analysis of Data

Chapter Structure

8.1 Introduction

In this chapter, the research collates the significant volume of relevant data collected and observed in the course of the investigation from multiple sources:

- PESTLE Analysis (external factors)
- Analysis of Rail Industry (internal factors)
- Online Survey (quantitative data – 202 responses)
- Key Actor Interviews (qualitative data – 43 interviews)
- Case studies (UK + Europe)

The data has been integrated, and an initial descriptive analysis has been undertaken; this analysis was used to inform several relevant case studies. The synthesis and critical analysis of this data for the research can now be undertaken. The overall research methodology for this project, illustrating the process for data collection, integration, and analysis is summarised in figure 8.1.

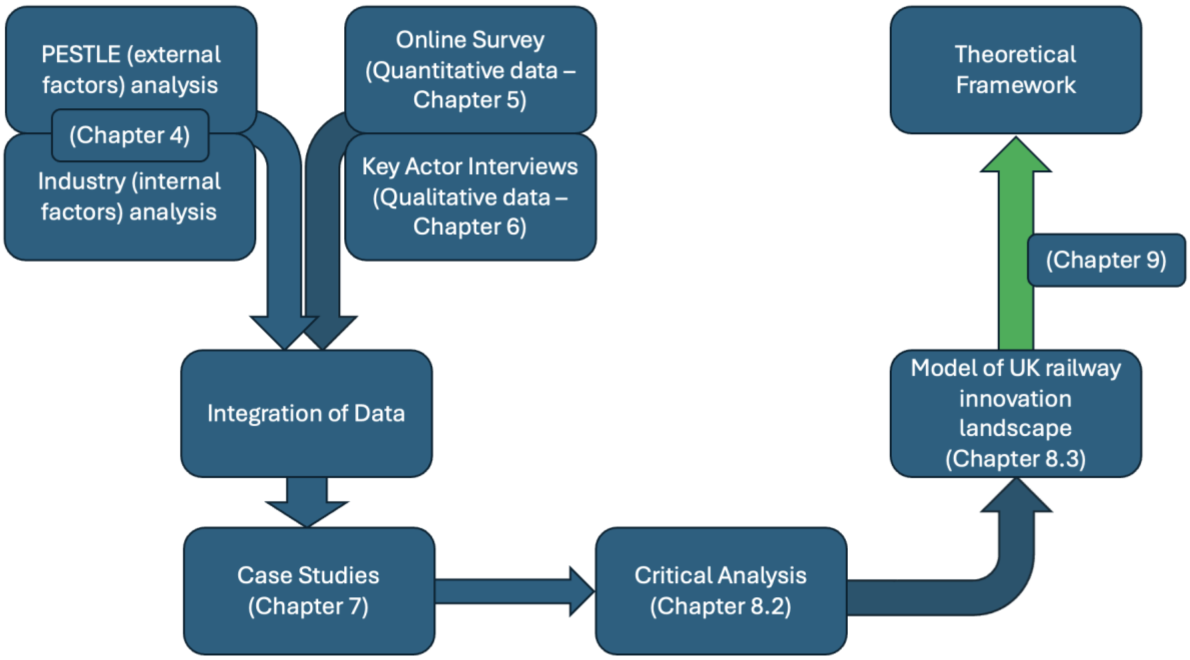

Figure 8.1: Summary of research methodology

8.2 Synthesis and Critical Analysis of Data Sources

To undertake a critical analysis of the data, it is useful to provide an overview of the findings. To do this, a high-level summary has been produced that builds on the integration of the data from the multiple sources, this is shown in figure 8.2.

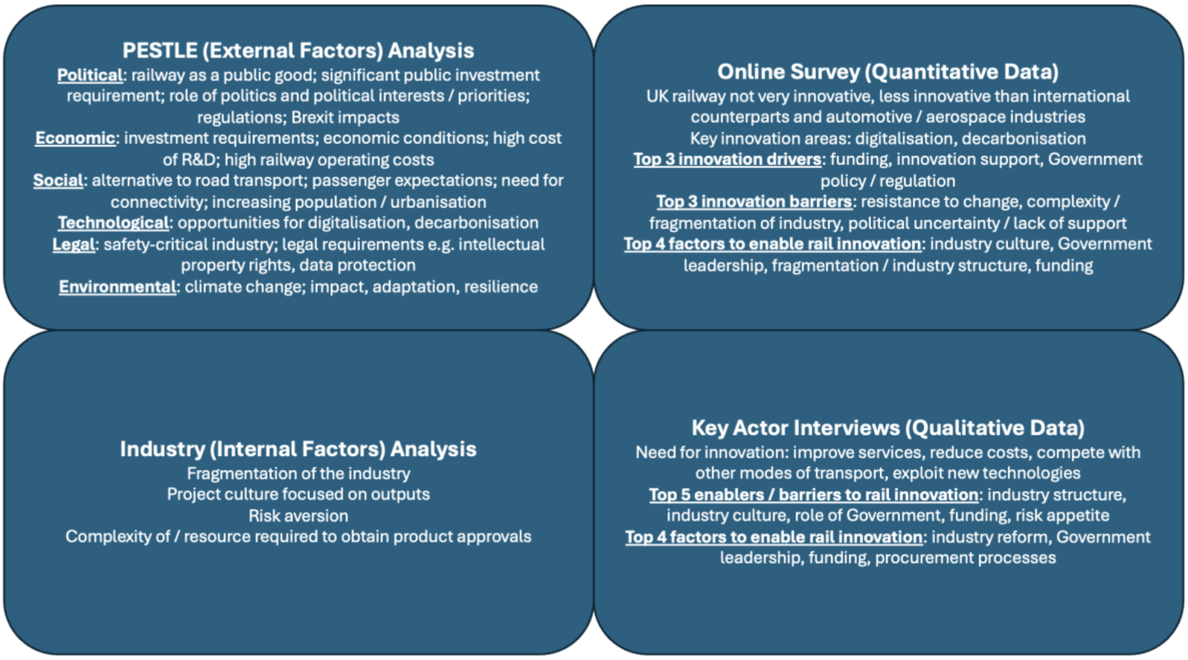

Figure 8.2: High-level summary of findings from research data

In addition to this high-level summary, the research has also identified nine themes that emerged from the key actor interviews, which were: the role and purpose of innovation in rail; the ability to innovate and openness to innovation; industry structure and fragmentation; the culture of the rail industry; risk appetite and costs of / benefits from innovation; the availability of funding; the availability of skills; the availability of support and facilities; the role of government and client bodies.

An analysis of the findings from across the sources of data finds several core themes emerging which can be summarised as:

(1) There are three core structural issues:

   a. The structure of the industry is a barrier to innovation.

The structure and complexity of the UK railway industry, and the fragmentation of roles and responsibilities within that, is a critical structural problem that blocks innovation. Respondents to the online survey, and key actor interviewees, cited this as a major barrier to innovation. The complexity of the industry makes it hard for new entrants to understand who does what and how it matters in the context of product approvals, market demand, economic buying power, decision-making, and ultimately the direction of the railway in what is considered state of the art and the technological direction of the railway.

b. The culture of the industry is not sufficiently open to innovation.

The UK railway industry is resistant to change and is a relatively closed and insular industry, where personal relationships are a critical part of doing business. This makes not just challenging the status quo difficult but also making bold decisions to adopt new strategies and technologies. As one interviewee said, "*challenging the orthodoxy is the hardest part*!" (from Group 'ST'); but another was even more direct, "the industry has to accept people that view rail as a career, and not just those with multiple generations of family history on the railways!" (from Group 'ST').

Another interviewee identified the difficulty in innovations breaking into rail from small organisations or from outside of the industry, "There is no space for pilot projects to shape and drive innovation, innovation only seems able to come from the centre (basically from Network Rail)" (from Group 'SI').

c. The nature of the railway as a public good requires active Government support and investment, this in turn can act as an enabler to innovation.

The importance of funding cannot be understated when it comes to enabling innovation. The cost and time required to successfully develop and commercialise innovations on the UK railway were frequently cited as a major barrier to innovation, and also as a critical means that could be a major enabler of innovation as well (from both the survey and interviews).

Several interviewees raised the potential for an openness to using small pilot projects to unlock potential innovations. The use of demand-led innovation challenges was identified as a means of opening up prospects for the acceptance of innovations where they solved a specific pain-point.

(2) There are three further factors that stem from those structural issues and manifest in demand-side barriers:

a. The rail industry is too averse to risk to be able to actively drive (and benefit from) innovation.

Risk aversion was identified as one of the four internal industry factors that acted as a barrier to innovation. It was also raised by the majority of key actors in interviews as a specific industry problem. On one hand, it is a factor of the industry culture problem, although it is tangibly manifested in the standards and product approvals regimes that set out detailed and complex requirements which put up a significant regulatory barrier to new solutions, particularly from suppliers with little experience of the rail sector.

It is important to refer at this point back to the online survey where respondents clearly described the railway as less innovative than the automotive sector (83%) and the aerospace sector (75%) – both of which are industries with strong regulatory regimes and safety-critical operations placing requirements on suppliers and manufacturers.

b. The key barriers to innovation – product approvals, standards, testing and validation - are too focused on mitigating risk and do not take of account of innovation need.

Building on the previous point, a recurring theme from the key actor interviews was the imbalance between risk and opportunity. The need for innovation to reduce costs and improve operations was unanimous, but innovative solutions struggle to enter the market and provide these progressive shifts forwards to accrue these benefits.

From the online survey, only 17% of respondents cited safety / standards as one of the top three barriers to innovation, 37% listed the high costs of R&D / market entry, which is a parallel factor in bringing innovations to market. Those high costs incorporate meeting the requirements of the standards and safety regimes, while further including the costs of development, testing, validation, and commercialisation more broadly.

Three interviewees went into significant detail about the history of rail regulation from the era of privatisation, and the impact of several horrendous rail accidents that took place (Southall 1997, Ladbroke Grove 1999, Hatfield 2000, Great Heck 2001, Potters Bar 2002) that formed a generation of railway industry workers. All three interviewees highlighted this period as establishing a mindset of safety-first and safety at all costs, creating a barrier to innovation that is dogmatic rather than pragmatic.

c. The industry does not challenge itself to address structural issues that block opportunities to develop and improve through the use of innovation.

The third of these demand-side factors focuses on the industry itself as acquiescing to a dogmatic approach to risk management and accepting it as the cost required to operate safely and correctly.

Referring back to the models of innovation and the multi-level perspective, the railway industry - as a socio-technical regime - has an established and accepted set of technological systems and practices. These have been recognised as being sufficient to meet and manage safety requirements. The issue is that the bar is set too high for any improvements or adaptations to these systems. The three interviewees who went into significant detail on the role of the early privatisation era as being a strong influencing in shaping the requirements and expectations of a safety regime, and its role as a barrier to innovation, reflect a constructivist interpretation of railway innovation as a human activity where technological developments are merely the object of actors identifying problems and using innovative solutions to solve them. This contrasts with the overriding industry culture that sees innovation *in itself* as a potential risk, rather than offering potential solutions to existing pain-points (such as the need to reduce costs and improve performance).

(3) Finally, there are three broad themes that are corresponding opportunities to address the demand-side issues:
    a. The railway has a huge opportunity to use technological advancements, particularly around digitalisation and decarbonisation, to use innovation to drive significant improvements and benefits.

Technological progress and the opportunities that new technologies can offer to the railway were recognised by both the online survey and the key actor interviews as a key opportunity to help the railway address its overarching challenges of reducing cost and improving performance. The PESTLE analysis identified the decarbonisation credentials and opportunities for the railway as significant across a number of relevant political, social, technological, and environmental external factors.

The case studies investigated in chapter 7 also demonstrate the breadth of potential opportunities for the railway to further decarbonise and provide policy options for governments to use railway investment and support to address the issue of climate change and the mission to address it and mitigate it.

b. Industry reform, with the support of government, can open opportunities for innovation by addressing the funding and fragmentation issues that block innovation.

The fragmentation of the industry, combined with political uncertainty, creates a vacuum of leadership and a lack of a coherent strategy for the role and purpose of the railway. However, effective industry reform combined with firm and consistent Government support can provide long-term certainty and clarity.

Almost all the key actors interviewed talked about the significance of the role of the Government in enabling railway innovation, and almost all of them used the word 'leadership'. As a public good, and a critical national infrastructure network, the railway is a strategic asset that the Government controls and directs given its significance to the health and wealth of the country – and has a key role in supporting a number of social, economic, and environmental policy objectives. If industry reform can be delivered effectively, the opportunity to incorporate design that can enable innovation is an opportunity not to be missed.

c. Openness to innovation and reducing barriers to innovation can be overcome through a mixture of policy instruments and initiatives.

The industry's resistance to change was cited as the biggest barrier to innovation by online survey respondents, while industry culture was described by the key actor interviewees as the second biggest barrier to railway innovation (after industry structure).

While a culture evolves incrementally, the structure can be adapted more rapidly and can be designed to create a greater openness to innovation structurally using policy instruments and initiatives. Funding is clearly the most obvious instrument, other enablers raised by the data include the provision of innovation support (such as peer and advice networks, better access to relevant information, testing facilities and support, meet the buyer opportunities), and the use of pilot projects to test and demonstrate innovative solutions to actual problems – these were described several times by interviewees as "no regrets projects" where the cost was relatively small for the potential gains that could be delivered. This analysis is summarised in figure 8.3.

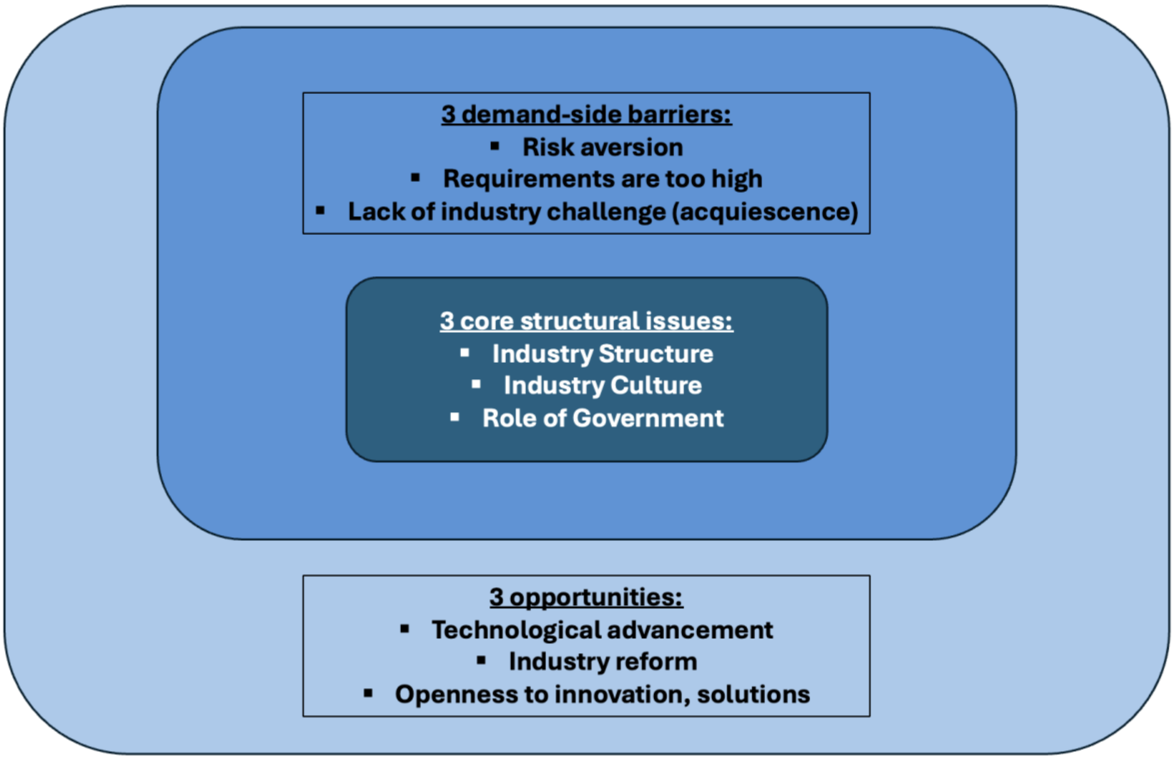

Figure 8.3: Summary of analysis

8.3 Model of UK Railway Innovation Landscape

The research has collected a significant volume of data, using mixed research methods, to undertake a detailed analysis of the UK railway innovation landscape. The purpose of this has been to build a model of how the UK railway innovation landscape can be described as it is. This model is required to then build a theoretical framework of how the UK railway innovation landscape ought to be, in order to deliver the objective of enabling more innovations onto the railway to meet the twin political requirements of improving performance and reducing operating costs.

The model builds from the literature review undertaken in chapter 2, as well as the data collected and analysed in this chapter. The key premises for constructing the model are:

(1) The importance of actors, networks, and institutions, in understanding the UK railway innovation landscape.

(2) The respective roles of the supply side and the demand side in describing how UK railway innovation happens.

(3) The use of the multi-level perspective framework - identifying and utilising the roles of the landscape, the socio-technical regime, and the niches, to develop the model of the UK railway innovation landscape.

(4) The context of the UK railway industry - incorporating the knowledge from the outputs of the PESTLE external factors influencing the railway, the four internal factors, the qualitative and quantitative data collected, and the historical context and development of the railway.

In figure 8.4, the model of the UK railway innovation landscape as it currently appears is set out.

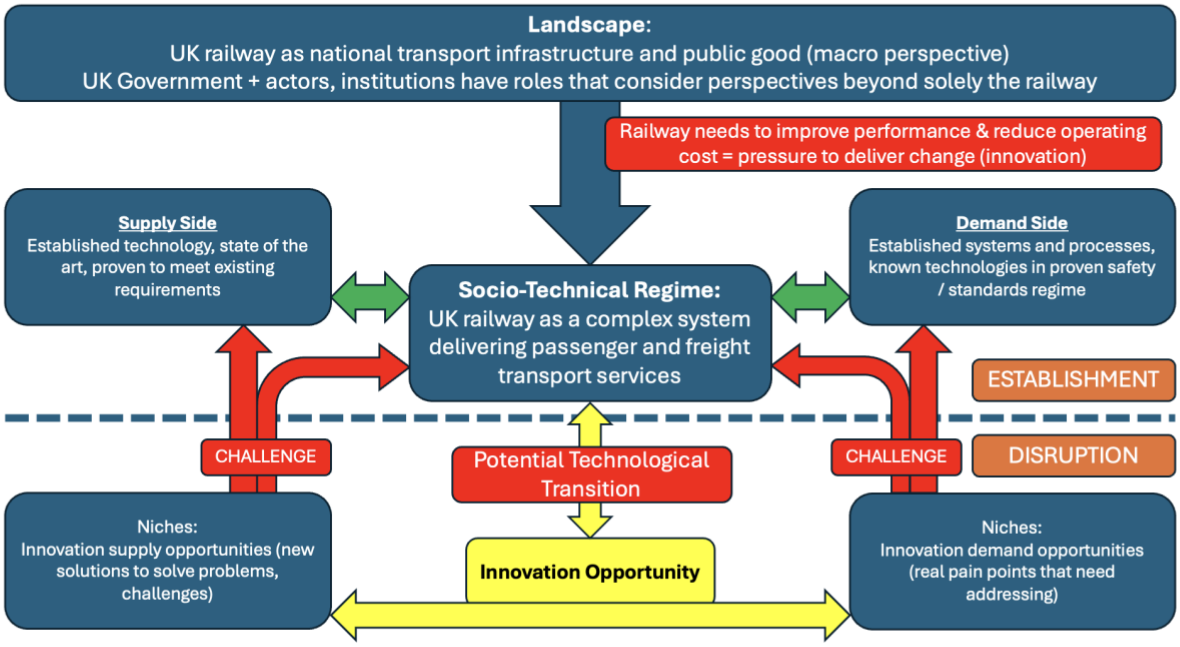

Figure 8.4: Model of the UK railway innovation landscape

This model of the UK railway innovation landscape reflects the learning from the data collected and the literature review to provide a descriptive analytical model. It is very purposefully split into two distinct sections:

(1) Above the hatched line, the 'establishment' section which comprises the wider Landscape incorporating the broader context within which the UK railway operates. This section also includes the UK railway as a distinct socio-technical regime, with technical norms established and proven and known technologies in widespread deployment. Furthermore, there are the supply and demand sides which are the railway supply industry and the railway operations industry respectively, working

together to provide passenger and freight services using the national railway infrastructure.

(2) Below the hatched line, the 'disruption' section which comprises supply and demand side innovation opportunities. The innovation supply grouping is focused on developing solutions to problems, while the innovation demand grouping is focused on solving real problems by identifying potential solutions. In recognising that innovation can be driven by a combination of supply side and demand side actors, the innovation opportunity sits in the middle looking for an opportunity to push the technological norms forwards with the adoption of new technology by the railway (through the process of a technological transition).

Underpinning this model is the recognition of two key learnings from the literature:

(1) The role of actors and institutions throughout the operation of this model of the UK railway innovation landscape is vital.

(2) The importance of the role of those actors and institutions compared to the intrinsic importance of the technology. The innovation is important because of its ability to solve problems or pain-points for actors involved in running the railway (as a socio-technical regime), it is not important as a means of implementing technology but through the outcomes that the innovation delivers and the benefits it provides.

8.4 Chapter Summary

In this chapter, the data has been collected, described, integrated, and analysed. The research has sought to establish a broad evidence base with a range of data sources used, including:

- Primary data:
  - Quantitative data from online survey
  - Qualitative data from key actor interviews
- Secondary data:
  - PESTLE (external factors) analysis
  - Industry (internal factors) analysis
  - UK and European case studies

From this data, a model of the UK railway innovation landscape has been constructed to provide a descriptive analysis of the current situation. In the next chapter, this model will be used to develop a theoretical framework for UK railway innovation that can better enable innovation to take place and be successfully realised.

Chapter 9: Introducing the Framework

Chapter Structure

9.1 Introduction

From the work so far, the research has brought together a number of key learnings to inform the development of a conceptual framework to be designed that builds on a model of the UK railway innovation landscape to identify measures to enable more innovation to successfully be introduced onto the railway.

In Chapter 2, the review of literature on innovation models and the application to the railway identified three critical learnings:

Firstly, the importance of considering innovation supply and demand perspectives within a broader view of the innovation system of actors and institutions who have a role or influence in the innovation landscape.

Secondly, that innovation is a cyclical rather than linear process that can be understood through the perspective of three layers - the landscape, the socio-technical regime, and the niches, which group together the actors and influences in the innovation landscape. Alongside these three layers are the phases of the innovation cycle, seen within the context of a socio-technical regime, which are the present landscape (that could also be described as the accepted state of the art), the design and development of the technology (supply side) and the corresponding 'need context' for innovation (demand side), and the outcome delivery as a result of the technological transition (the introduction and acceptance of innovation, moving the state of the art forwards).

Thirdly, that there are three fundamental and concurrent parts and roles to the innovation process cycle, described as:

(1) Technical – a supply side perspective, considering what can be done and by whom.
(2) Contextual – a demand side perspective, considering problems that need addressing, and what can be accepted.
(3) Institutional – a blended perspective, considering the interactions between all relevant actors and with a broader perspective of the overarching landscape.

Chapter 3 built on those learnings to understand the Need, Problem, Question, and Objective for the research that a conceptual framework can assist in providing a solution to the research thesis. This guided our analyses of the UK railway innovation landscape to gain a deeper understanding of the UK railway and the context for innovation.

Chapter 6 further enhanced and verified those learnings through a series of interviews with key actors providing qualitative data, supported by a larger online survey providing quantitative data (chapter 5). These learnings were illustrated with a number of case studies in the field of alternative railway traction systems to analyse and understand the range of factors impacting on innovation in this space (chapter 7).

This research is using a systems approach to the structure of the research, in this chapter the research focuses on the Implementation section – as illustrated in the table below.

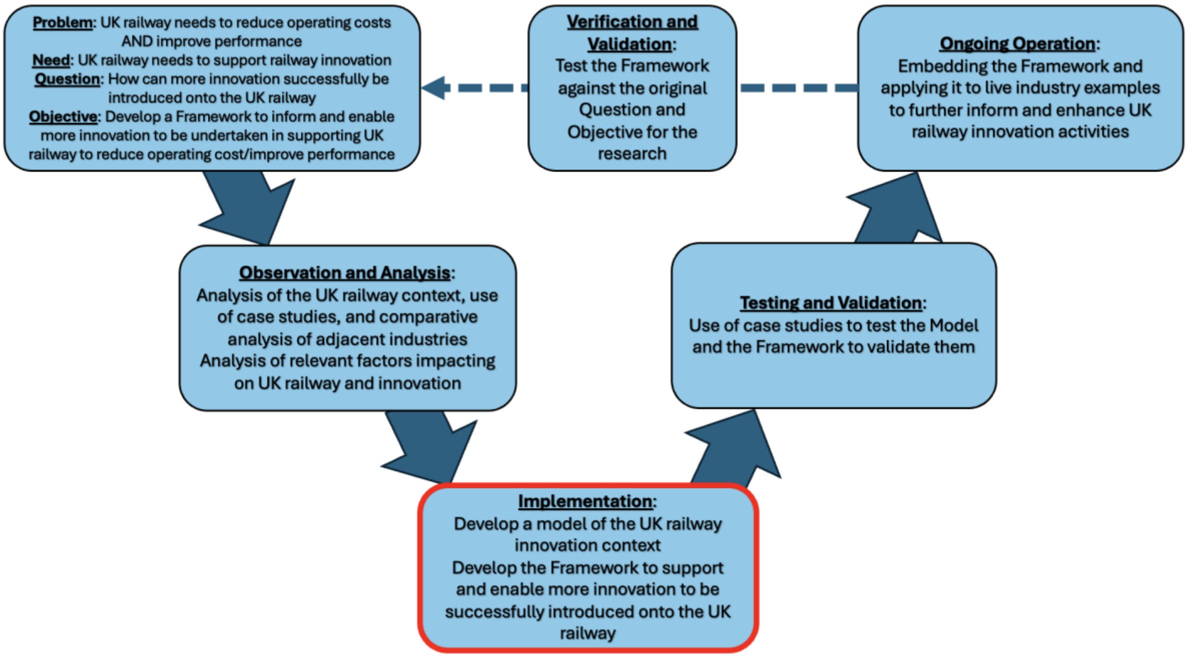

Figure 9.1: Systems approach to this research (with relevant section for Chapter 9 highlighted)

Chapter 8 concluded with the design of a model of the UK railway innovation landscape, that was designed to illustrate and summarise how the UK railway landscape can best be described using the learnings from the research (see figure 8.4, reproduced below).

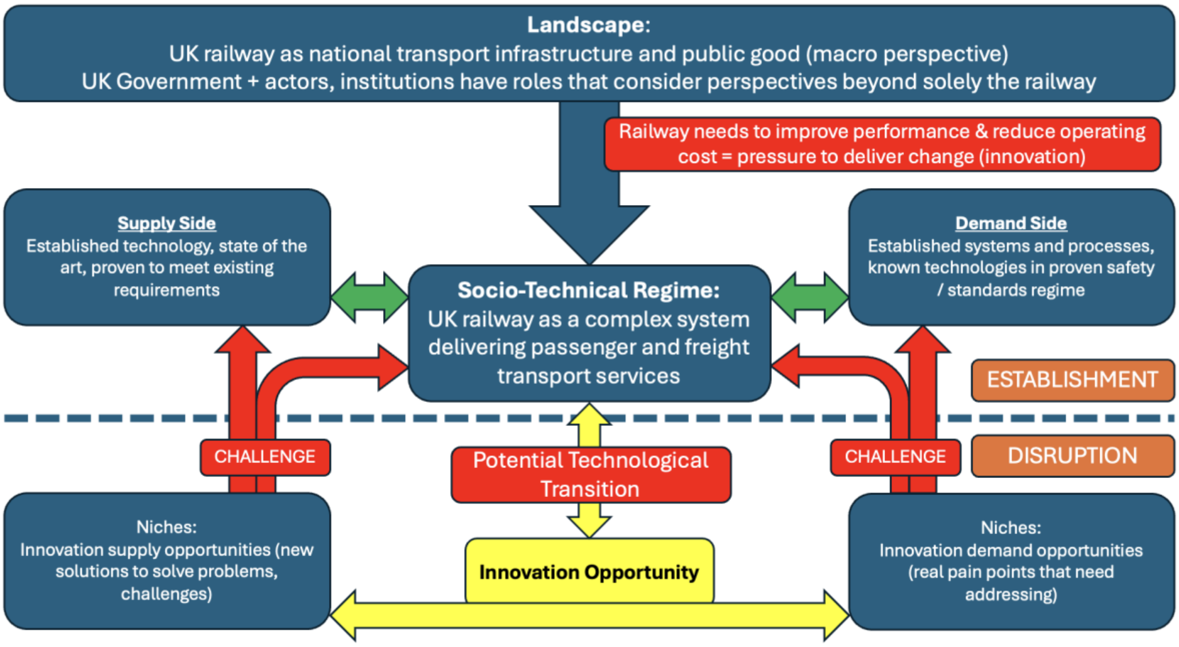

Figure 8.4: Model of the UK railway innovation landscape

9.2 A Conceptual Framework of the UK railway innovation landscape

The objective of this research is to develop a conceptual framework of the UK railway innovation landscape that can enable the more successful introduction of innovation onto the railway (section 1.3 and Research Question 5). In this section, the findings from the literature review and all the data collected will be used to create this framework.

9.2.1 Key inputs into the conceptual framework

The inputs into the conceptual framework to aid the design are now summarised in two parts, firstly the theoretical inputs from the literature review in chapter 2, and then the data inputs from the observation and analysis in chapters 4-7.

9.2.1.1 Theoretical inputs

Key outputs from the literature review were derived from several theories and models of innovation including open innovation, mission-oriented innovation, the multi-level perspective, innovation systems, and social construction.

The conceptual framework must recognise the importance of considering innovation supply and demand perspectives within a broader view of the innovation system of actors and institutions who have a role or influence in the innovation landscape. The role of actors and networks within railway innovation is critical to understanding and explaining both how innovation actually happens, as well as where the barriers and enablers exist.

The framework must also recognise that innovation can be viewed as a cyclical rather than a linear process with three layers – the landscape, the socio-technical regime, and the niches - which support the identification and roles of the relevant actors and their influences in the innovation landscape.

Additionally, three phases of the innovation cycle can be identified, seen within the context of a socio-technical regime – the present landscape or state of the art which is the established technology that is used and understood by the socio-technical regime, the development phase of both the technology (supply side) and the commercial context (demand side) that provide the opportunity for the innovation to enter the landscape, and the successful introduction of the innovation delivered onto the railway. Crucially, as a result of that successful introduction, the innovation sets a technological transition whereby it moves from a technical niche to establish a new state of the art and therefore becomes an established technical norm within the socio-technical regime - this is illustrated in figure 9.2.

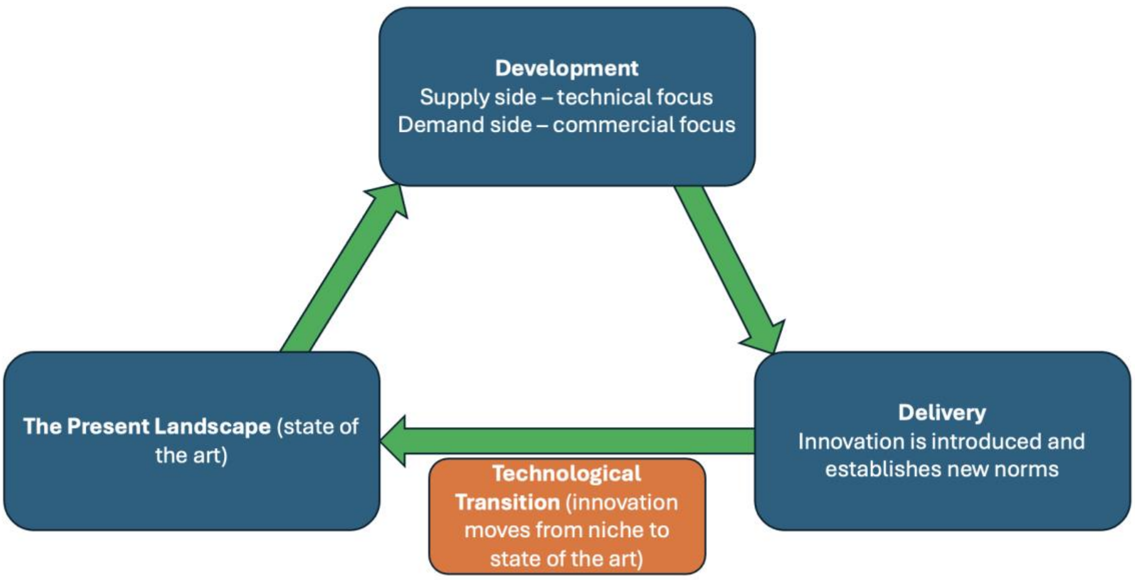

Figure 9.2: Three phases of the innovation cycle

Alongside those three phases of the innovation cycle, there are three fundamental and concurrent parts or roles to the innovation process. Firstly, there is the technical role – a supply side perspective, considering what can be done and by whom to develop and deliver improvements to the current state of the art. Secondly, there is a contextual role – a demand side perspective, considering the problems that need addressing, the commercial need, and the pragmatic perspective of what can be accepted. Finally, there is an institutional role – this can be described as a blended perspective, considering the roles, requirements, and interactions between all relevant actors and networks within the broader perspective of the overarching landscape (beyond just the socio-technical regime).

9.2.1.2 Data inputs

Key findings from the data were generated across the full range of data inputs collected and are summarised in figure 8.2, reproduced below.

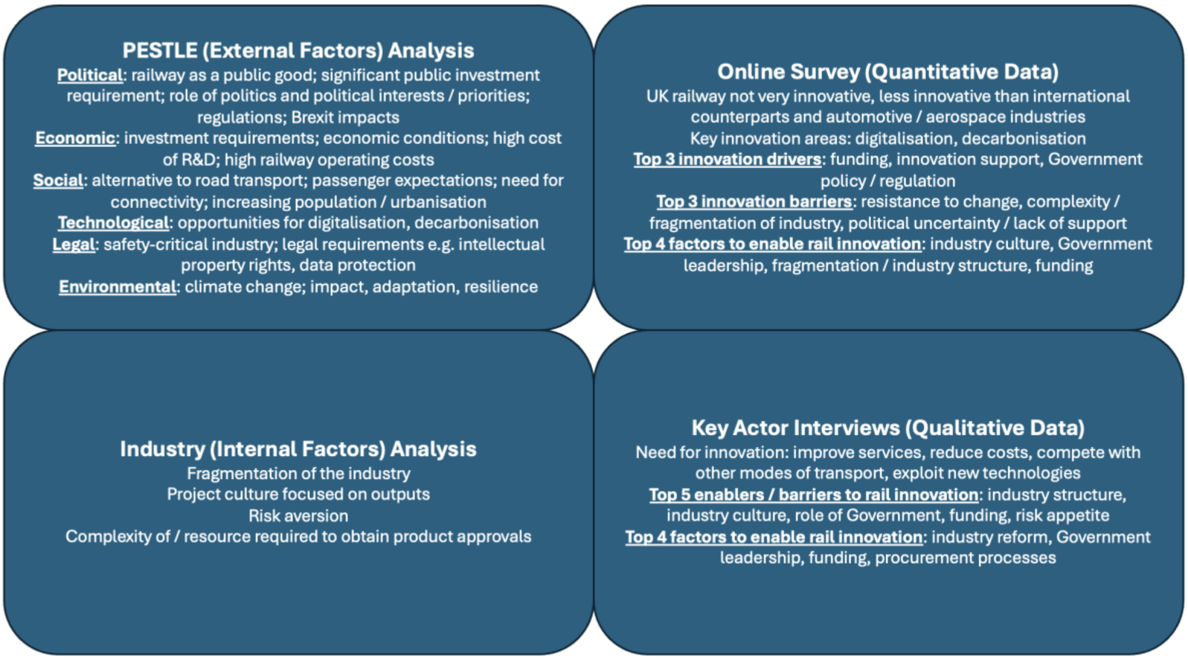

Figure 8.2: High-level summary of findings from research data

Building on this summary, the conceptual framework recognises the role and influence of the key actors in the UK railway innovation landscape, alongside identifying the relevant barriers and enablers that play significant roles in the successful introduction of innovation onto the UK railway.

Across the data collected, the central recurring themes were clearly identifiable as six key factors that influence the success of UK railway innovation – the structure and fragmentation of the UK railway industry, the culture of the UK railway industry, the role of the UK Government, the need for funding, the appetite for risk, and the need for innovation support. Table 9.1 sets out these themes.

Key Themes	Data sources
The structure and fragmentation of the UK railway industry	The PESTLE analysis raised this as a political issue. This was also identified as an internal factor for the industry. The quantitative and qualitative data both highlighted this as a major factor.
The culture of the UK railway industry	This was identified as an internal factor for the industry. The quantitative and qualitative data both highlighted this as a major factor.
The role of the UK Government	The PESTLE analysis raised this as a political issue. The quantitative and qualitative data both highlighted this as a major factor.
The need for funding	The PESTLE analysis raised this as a political and economic issue. The quantitative and qualitative data both highlighted this as a major factor.
The appetite for risk	This was identified as an internal factor for the industry.

	The quantitative and qualitative data both highlighted this as a major factor.
The need for innovation support	This was identified as an internal factor for the industry. The quantitative and qualitative data both highlighted this as a major factor.

Table 9.1: Six key factors influencing success of UK railway innovation

These six factors combined enable a conceptual framework to be produced that utilises the model of how the UK railway innovation landscape is to address the barriers, highlight the potential enablers, and create a framework for how to enhance the opportunities for successfully introducing innovation onto the UK railway.

9.2.2 The Conceptual Framework

9.2.2.1 A Current Framework

The proposed conceptual framework builds on the model of the UK railway innovation landscape (see figure 8.4 above). To begin with, the model is adapted to create a framework of the current UK railway innovation landscape (see figure 9.3 below).

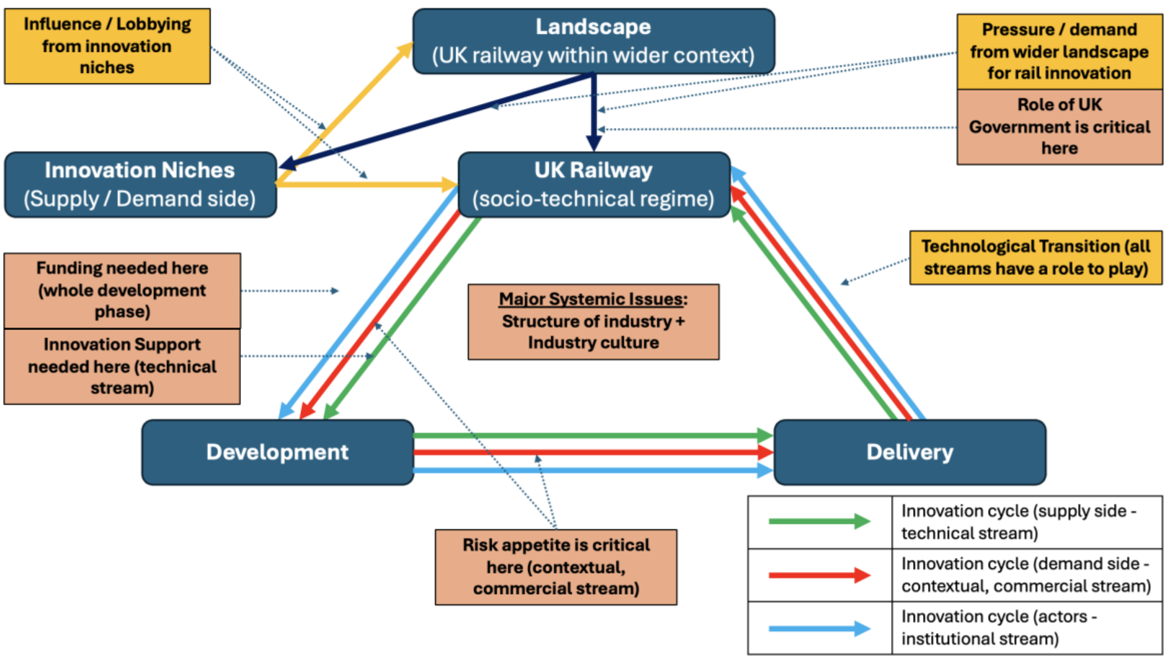

Figure 9.3: A current framework of the UK railway innovation landscape

This framework provides a conceptual analysis of how UK railway innovation currently takes place, building on the models and theories of innovation from chapter 2 and the observation and analysis of the data collected in chapters 4-7.

The three streams of activities and actors are highlighted within the phases of the innovation cycle:

- The innovation supply side, comprising the technical and commercial capabilities and objectives that drive the development of innovative solutions to move technical norms forwards to deliver an improved railway (ie better services, reduced operating costs, better safety and reliability).
- The innovation demand side, comprising the operational and commercial capabilities and objectives that deliver railway services to passenger and freight customers. This contextual stream is the delivery of the operating railway as required by the UK Government for the greater good of the country as a critical piece of national infrastructure.
- The institutional stream that comprises the wider stakeholders and interests in railway innovation, comprising actors with roles and influence on either or both of the supply and demand sides, including researchers, investors, politicians, local government, the media, and many others who can have an influence on the railway innovation landscape.

The innovation niches are drawn out from the model as playing a key driving, disruptive role in placing innovation on the agenda of both the railway sector (as a socio-technical regime) and the wider landscape (ie political and other actors who have significant influence on the likely prospects of innovations being considered). As shown in the model (figure 8.4), these niches are not just supply-side inventors but can also include demand side disruptors who need solutions to address real or potential problems. The demand side niches are particularly key in the rail sector as a counterweight to the clearly identified issue of the culture of the rail industry being particularly resistant to change (strongly identified in the quantitative data, as well as the qualitative data).

The six key factors influencing the success of UK railway innovation (see table 9.1) are also highlighted within this framework. Four of these factors are specific functions within the innovation cycle, three of which (funding, risk, innovation support) are generic to many other sectors, while the fourth (role of UK Government) is key to rail and a number of other industries (for example aerospace) where there is a significant legal and regulatory role for the Government across the sector. The other two factors (industry structure and industry culture) are identified as major systemic issues that play an influential role throughout the innovation cycle and are a specific issue to the UK railway industry.

9.2.2.2 A Conceptual Framework

From the current framework of the UK railway innovation landscape, a conceptual framework that can address the identified issues and provide an enhancement to the likely success of innovation can now be constructed.

This conceptual framework has three fundamental areas to address within the current framework to provide the shift towards greater support and enabling of innovations to break through and be introduced onto the UK railway.

Firstly, the structure of the railway must be addressed. The fragmentation of the sector and the misalignment of costs and benefits, as well as responsibilities and opportunities, are systemic barriers to successful innovation.

Secondly, the backing for innovation must exist. This element is a mix of both culture and instruments. The culture of the industry stems, to a certain extent, from the issues with the structure – improved alignment of responsibilities and incentives can foster a more supportive culture towards innovation; this can also address the aversion to risk and the project output focus that was also identified as an internal factor influencing innovation. The instruments to enable innovation include the availability of funding, a drive to initiate pilot projects to test and demonstrate innovation opportunities, and wider innovation support such as innovation expertise to drive innovation projects through development more quickly and efficiently, testing and validation facilities and support, and commercialisation and market entry support.

Thirdly, an openness to innovation and a positive culture of change needs to be embedded within the industry. This reflects the two major systemic issues – industry culture and industry structure – as well as the critical role of the UK Government and its overwhelming influence on the UK railway. The role of innovation to deliver tangible improvements that are required by the Government as the ultimate owner, funder, and controller of the UK railway is patently clear. That innovation is not necessarily just new products and solutions but also incorporates opportunities to develop and deploy innovation in policy, funding and financing mechanisms, business cases, legal and regulatory requirements, technical standards, product approvals, and so on.

Figure 9.4 sets out the proposed conceptual framework.

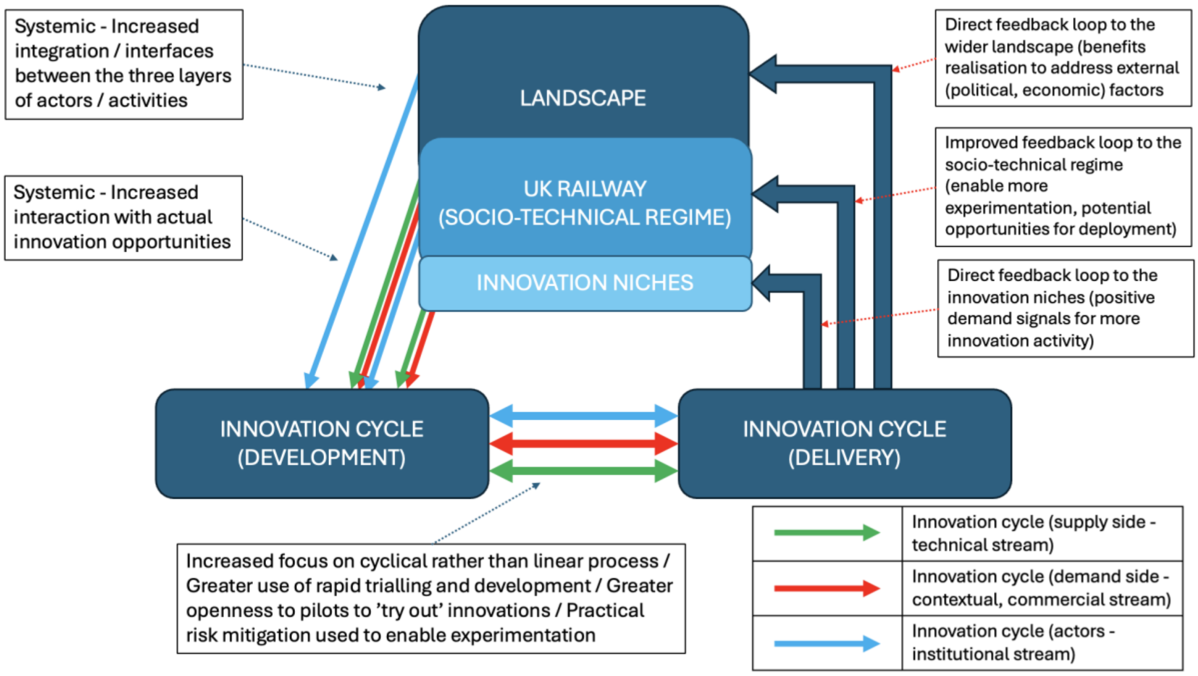

Figure 9.4: The conceptual framework

The framework uses the innovation cycle model and purposefully incorporates the multi-level perspective as well as using learning from the innovation systems and social construction theories of innovation. Importantly, the potential for open innovation and mission-oriented innovation to drive supply and demand innovation activities respectively is also clearly possible.

The framework addresses the two major systemic issues (industry structure and culture) by factoring in the opportunity for more direct interfaces between the development phase of the innovation cycle and the present context, particularly by a wider set of actors and especially the wider landscape the broader range of stakeholders within the institutional stream.

The development and delivery phases of the innovation cycle are structured as ongoing loops that must enable greater and more rapid innovation activity, focusing on providing the funding and space for more experimentation. A critical gap within the industry culture is the trust and confidence to be able to experiment with potential solutions to give them the opportunity to be proven at an earlier stage of the development cycle.

The final phase of delivery and technological transition as new solutions are adopted requires a much stronger focus on assessing, measuring, and disseminating the realisation of benefits and practical outcomes derived from the innovation deployment. This element consists of three levels of feedback:

- Firstly, the feedback at the institutional level – that the innovation deployment has delivered tangible benefits, enabling the Government in particular to see the railway delivering improvements and providing credible evidence of success in using innovation to deliver the sought after outcomes (i.e. improved performance and/or reduced operating costs).
- Secondly, the feedback at the socio-technical regime level – that the innovative solutions have delivered benefits, and also that the process has enabled successful innovation. This is a key element in addressing the issue of industry culture and generating a shift in mindset from resistant to enabling.
- Thirdly, the feedback to the innovation niches – these are key in providing positive signals that innovation is wanted and needed, and that the risk in undertaking innovation is justified by the existence of tangible demand for new solutions.

The conceptual framework is purposefully simple in structure (a 3x3 matrix) and can be broken down into component parts:

Temporal – three phases of the innovation cycle – these are shown in dark blue (the boxes titled Landscape, Development, and Delivery).

- Present context, the use of the state of the art, delivering the existing technology within established technical norms.
- Development – the push/pull for innovation from the supply/demand sides to address real problems, incorporating product development and testing, from both the technical and commercial/operational contexts.
- Delivery – the commercial and operational deployment of innovative solutions, and their integration onto the railway. Importantly, from here there is a clear feedback loop into the present context – this is the technological transition, where the innovative solution metamorphoses into the technical norm and becomes the established state of the art.

System layers – three streams of actors and roles – these are illustrated by the arrows moving round the cycle (green, blue, and red) reflecting the different groups of actors and their respective roles.

- Supply side (technical stream) – developing and promoting innovative solutions to improve the performance of the railway.
- Demand side (commercial, contextual stream) – operating the railway and experiencing the issues that innovative solutions aim to solve.
- Actors (institutional stream) – broader set of roles with influence on supply and demand sides, including the Government and a range of other external stakeholders.

Structural – three levels within the railway innovation environment – these levels are reflected at the Landscape element of the framework, as the 'starting point' of the analysis utilised by the conceptual framework.

- Landscape – the overarching context that the railway has a role within as critical national transport infrastructure, influenced by the external factors set out in the PESTLE analysis (see chapter 4).
- Socio-technical regime – the UK railway as a complex system itself, with a set of established institutions and norms.
- Niches – the drivers of innovation and disruption within the railway.

The proposed conceptual framework synthesises the learnings from the research and creates a simplified method for providing a structured insight of how UK railway innovation happens, focusing on key areas where the introduction of innovation can be de-risked and enabled to enhance its likelihood of success.

9.3 Chapter Summary

In this chapter, the proposed conceptual framework has been set out and described. In the next chapter, it will be tested and validated using a case study from chapter 7 in the field of sustainable railway traction power systems.

Chapter 10: Testing the Framework

Chapter Structure

10.1 Introduction

In this chapter, the research will undertake a practical application of the proposed conceptual framework to test and validate it. The HydroFLEX and HydroShunter case studies from chapter 7 will be used to illustrate the framework in the field of innovation in sustainable railway traction power systems. Figure 10.1 sets out how this fits within the systems approach to this research.

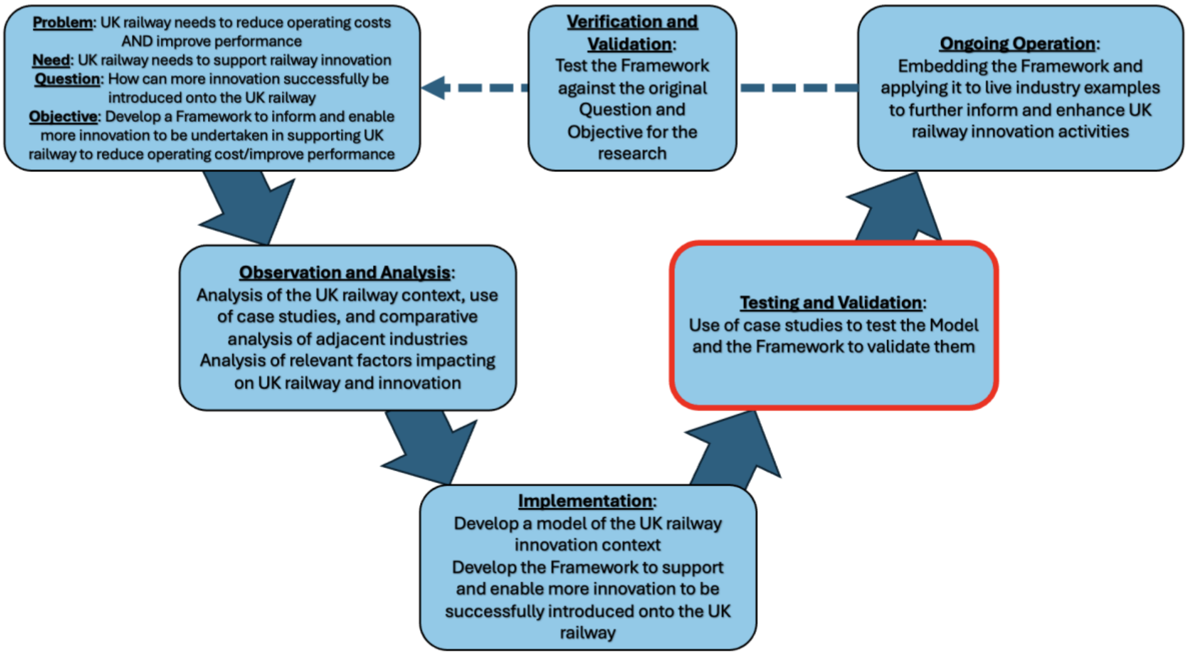

Figure 10.1 Systems approach to this research (with relevant section for Chapter 10 highlighted)

10.2 Practical application of the conceptual framework to the case study

The conceptual framework is now applied to the topic of innovation in sustainable railway traction power systems, and specifically the development of hydrogen traction power as a new solution to decarbonise the railway. The author has been practically involved with this case study over the last seven years as part of the research and innovation team that delivered the HydroFLEX project, that then formed a company to further develop and exploit the knowledge commercially, and the subsequent development of the HydroShunter project.

In 2016, Alstom launched the world's first hydrogen-powered train (see chapter 7.3.1) which captured the attention of the global rail industry as an opportunity to accelerate decarbonisation of the railway by phasing out diesel trains more quickly without the need for substantial investment in complete electrification of all railway infrastructure.

Subsequently, the UK Government expressed real interest in the potential application of this technology to the UK railway. In June 2018, the then-Secretary of State for Transport, Rt Hon Chris Grayling MP, met with the University of Birmingham team (including the author) to see a narrow-gauge hydrogen-powered locomotive to demonstrate the technological potential of hydrogen as a viable alternative to diesel as a source of traction power for the railway.

Figure 10.2: University of Birmingham team demonstrating 'Hydrogen Hero' to the UK Secretary of State for Transport at Rail Live 2018

The University team subsequently partnered with Porterbrook to scale up the traction technology to develop a prototype demonstrator of a full-sized railway rolling stock unit that would become the UK's first hydrogen-powered train – HydroFLEX that was successfully operated at Rail Live 2019. The unit was subsequently developed further, having successfully obtained innovation funding from Innovate UK, the Government's innovation funding agency, alongside significant matched private investment from Porterbook to enable a full operational demonstrator to obtain mainline approvals and become the UK's first mainline hydrogen train in 2020.

The HydroFLEX project has been ongoing for seven years. In 2025, the unit is in private operation and Porterbrook are seeking a commercial operator. However, external factors have played a significant role in stymying the deployment of this vehicle and the wider application of the technology in the UK.

Up to 2022, the UK Government had indicated tangible support for hydrogen as a technology to be applied to the railway – for example, in the Transport Decarbonisation Plan (Department for Transport 2021) and the Traction Decarbonisation Network Strategy (Network Rail 2020). This support however diminished due to three factors:

- Firstly, the external political and economic factors of limited public investment available to support the railway
- Secondly, the impact of the covid pandemic significantly reduced rail patronage and farebox revenue, requiring significant public subsidy just to keep the railway running – this pressure focused available investment on operations and maintenance alone, but left little for significant upgrades.
- Thirdly, the ongoing planning for rail reform and the future introduction of Great British Railways provided a primary focus for rail policy, as well as a planned change of actors and roles with responsibility for innovation to come, creating a hiatus for rail innovation at the time.

Following the development of the HydroFLEX project, the team established a partnership with the Severn Valley Railway, to retrofit a Class 08 diesel shunter locomotive with the hybrid hydrogen/battery technology to showcase its application in a railway locomotive – the HydroShunter project. The aim of this project was to demonstrate the practical application and opportunity for the technology to be used to decarbonise railway operations, and for the team to have greater control to showcase the technology to the market.

The HydroShunter was launched in early 2025 to the market (Rail Business UK 2025) with the aim of generating explicit market interest in a practical solution that was commercially available for use.

Figure 10.3: Launch photo of HydroShunter at Severn Valley Railway (January 2025)

The HydroFLEX and HydroShunter projects are closely linked, with the same core team (including the author of this research) involved in both major innovation projects. These projects will together provide the case studies to test and validate the practical application of the conceptual framework (in figure 9.4, reproduced below).

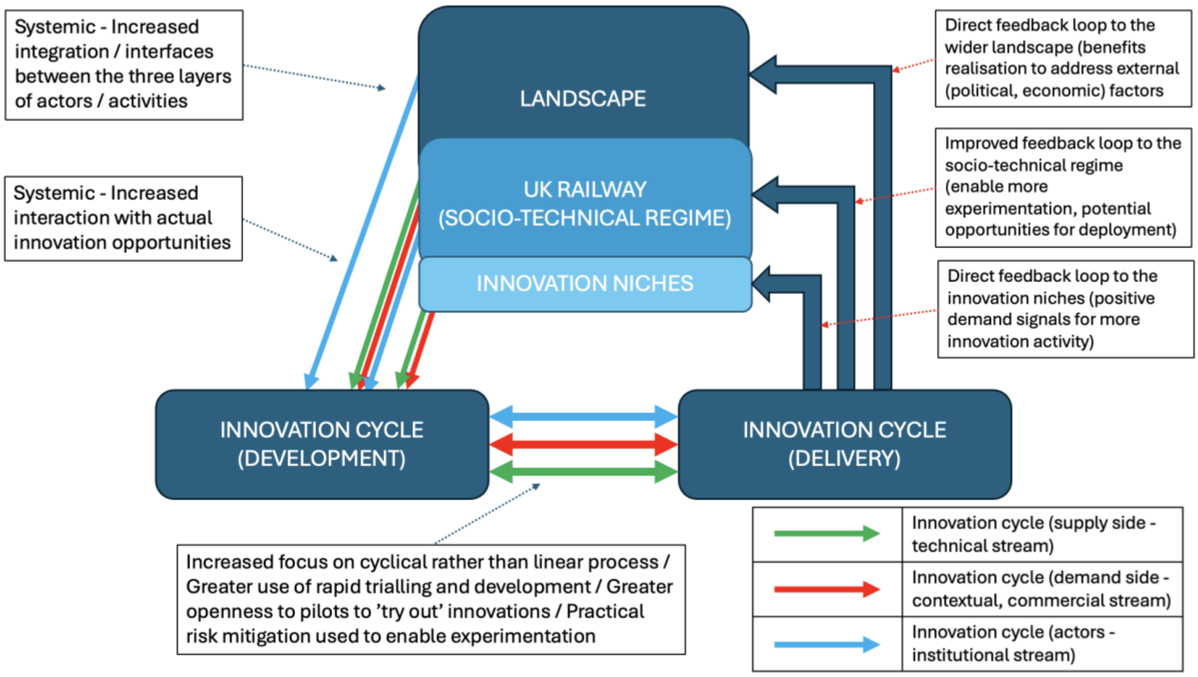

Figure 9.4: The conceptual framework

To test and validate the framework, it is proposed to work through the component parts of the 3x3 matrix, in order - the three phases of the innovation cycle; the three system layers (the actors/roles); and the three structural layers of the railway innovation environment.

(i) The three phases of the innovation cycle

The state of the art for railway traction systems in the UK at the time was a straight choice of electric traction where the infrastructure was electrified, or else diesel traction. In the wider context, transport decarbonisation was a key issue as the transport sector was the leading emitter of greenhouse gases. Railway infrastructure electrification was progressing extremely slowly, and the industry had lost credibility with the Government in delivering electrification effectively after the Great Western Electrification Programme had run significantly over time and budget.

The demand for alternative traction decarbonisation options existed, and the relevant actors and institutions expressed interest in seeing this developed. This was evidenced by the provision of Innovate UK funding and private funding for the HydroFLEX development work, and private funding for the HydroShunter project. The availability of funding and the political and institutional interest in both projects enabled their progression, while the development activities were enabled through an open innovation approach that brought in a wide range of expertise from across rail and hydrogen technology capabilities to collaborate in the effective delivery on the innovation projects.

With both products delivered, the key phase is the deployment and commercial application of the technology. While not yet state of the art in the UK, hydrogen and battery traction systems are becoming more widely adopted across Europe with hydrogen trains operating in Germany and soon to be operating in France and Italy, as well as in California, and with demonstrations undertaken in several other countries including Canada, Spain, Portugal, Netherlands, and Austria.

These market activities provide the feedback loops demonstrating the practical implementation and benefits of introducing the technology. They also give confidence to innovation suppliers that there is market demand for investing in the further development of products to support the wider adoption of the technology.

(ii) The system layers (the three streams of actors and roles)

The innovation supply side (the technical stream) in this practical application is the project delivery team and their broad range of collaborators and suppliers. Both projects used open innovation partnerships to drive the technical development to attempt to open the market by showing the capability and readiness of the technology for operational deployment.

The innovation demand side (the commercial, contextual stream) consists of the rail operators and infrastructure managers who need to deliver a decarbonised railway. The pressure remains on the railway to achieve net zero operations by 2050 and there is a clear need for the technology to be developed and deployed to achieve that objective.

The actors and stakeholders who comprise the institutional stream have a key role in these case studies. The political and economic external factors provide the policy demand and public funding that enabled the HydroFLEX project to secure the necessary investment to proceed (totally several millions of pounds over several years).

(iii) The Structural elements (the three levels within the railway innovation environment)

The wider landscape within which the railway operates is key to driving both hydrogen railway traction system projects. Political objectives to deliver environmental improvements to address climate change enabled economic support for these projects.

The UK railway as a socio-technical regime generally remains wedded to infrastructure electrification as the primary (and quite often viewed as the only) solution to decarbonise railway operations. However, this is not a pragmatic position to take as the rate of electrification is in no way likely to deliver a decarbonised railway in the timescales demanded from political stakeholders. The pressure from the wider landscape to pursue alternative traction technologies has been critical in pushing forward the development and testing of this technology.

The project team have driven the innovation niche for hydrogen traction power with partners and collaborators. As a disruptive influence, the team have worked to prove the applicability of the technology to attract economic and political support for the deployment of the technology.

Referring back to the conceptual framework, there are several observations that are relevant:

- At the start of the HydroFLEX project, there was a clear alignment across the three layers of actors and institutions – the push for transport decarbonisation was clearly coming from the UK Government (the wider landscape), and this was understood and accepted by the UK railway industry (the socio-technical regime). The rail industry was broadly open to new technologies, albeit with a clear preference for using the established technology of infrastructure electrification as the default option. The innovation niches were motivated and developing alternative solutions to support this ambition.
- The innovation niches had a relatively broad alliance across the supply side, demand side, and the institutional side, with a recognition that the novel solutions of battery and hydrogen could play a key role in delivering rail decarbonisation more quickly and cost-effectively. With the global manufacturers, Alstom followed by Siemens and CAF, all pursuing these technologies, the innovation niches in the UK knew that

this technological transition was not too disruptive to be actively considered and pursued.

- The field of sustainable traction systems (and equally digitalisation data) does have greater systemic integration and interfaces across the three layers of actors and institutions – the supply and demand sides are actively pursuing the digitalisation and decarbonisation agendas for rail. Given the third institutional layer has stated clear support, then it is apparent that the importance of that positive system-level interaction and integration is key to enabling innovation to be pursued.
- However, moving through the innovation cycle is more complicated as active support from across the three layers of actors remains vital and to go beyond words. At this point, more tangible enablers are required – funding, practical support, and active sponsorship of finding solutions to real problems. The HydroFLEX received public funding and vocal political support, the HydroShunter project was much less high profile. This highlights the importance of innovation project momentum – whereby project funding, practical support, and explicit demand is clearly available to pull a project through the cycle.
- Finally, the framework places great importance on the feedback and learning from innovation activity into each of those three layers. For HydroFLEX, the supply side learning has been significant with the project partners and supply chain learning a huge amount about the technology and about how to deploy it on the railway. The learnings have not yet reached the other streams as clearly – the demand side are receiving learnings, but key messages would include feedback on how to enable more innovation to increase the learning and verification of the technology and its applicability to various parts of railway operations. This would also be valuable to support the institutional stream in developing long-term strategy for the railway and broader rail policy development.

The framework draws out the key issues from the case study beyond the merely technical discussion of how to develop new solutions to address real problems. In particular, disruptive innovation is difficult to deploy onto the railway and the reason for this is the complexity of the railway landscape and the importance of the demand and institutional layers of actors who are key enablers or barriers.

10.3 Chapter Summary

In this chapter, the framework has been tested and verified using the case study of two hydrogen traction system innovation projects in the UK. These projects are valuable examples to use as they are recent examples of disruptive innovation requiring significant development for specific railway application. They clearly illustrate the importance of actors and institutions in UK railway innovation, and that it is not a transactional or simple commercial project to introduce innovation onto the railway, but in fact requires a much wider understanding of the UK railway as a complex system of operations, regulations, and actors and institutions.

Chapter 11: Verification and Conclusions

Chapter Structure

11.1 Introduction

In this final chapter of the research, the Conceptual Framework and case study are reviewed with reference to the observations and critical analysis from the preceding chapters and referring to the research objectives and questions. The conclusions from this review also identify areas for further research to further develop the framework and enhance our understanding in the field of railway innovation.

Referring to the research approach (chapter 1.5), the area highlighted in figure 11.1 sets out the objectives for this chapter to complete the systems model deployed for this research.

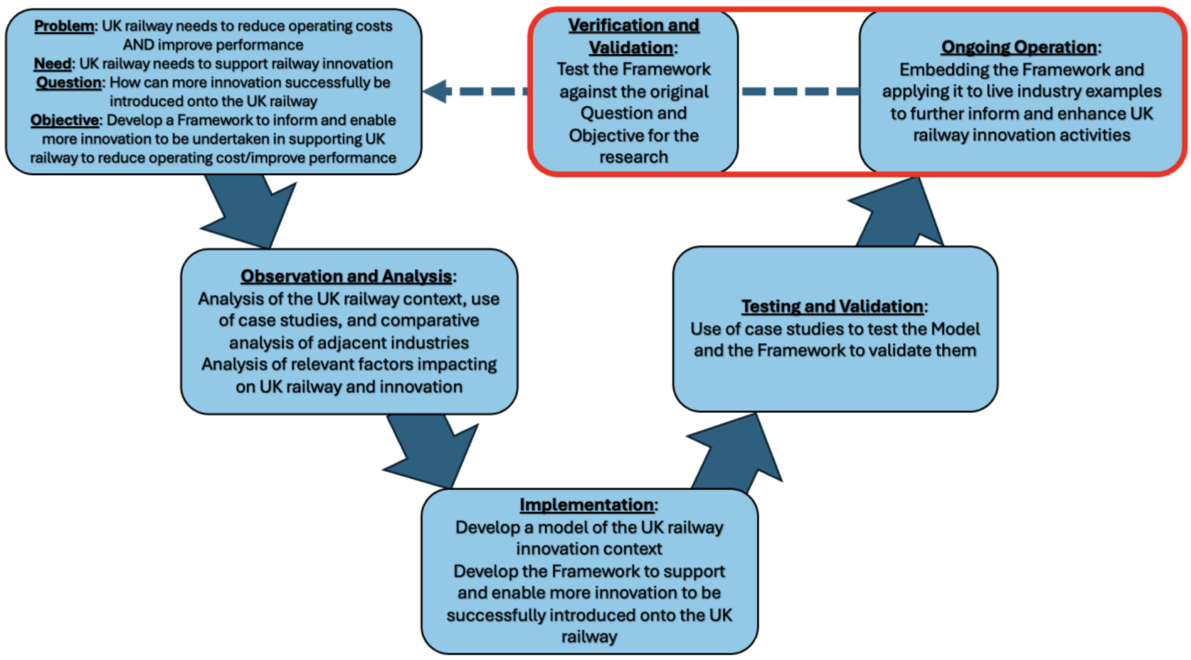

Figure 11.1: Systems approach to this research (with relevant section for Chapter 11 highlighted)

11.2 Verifying and validating the research

The research started out with the hypothesis that the UK railway needs to better enable more innovation to meet the major challenges it currently faces (the need to both improve performance and reduce operating costs). The conclusions from this research focus on developing new knowledge around whether innovation in rail is currently effective, how support could be better designed to enable greater likelihood of successful outcomes, and on whether current investment and organisations involved are effective in delivering innovation for the railway.

To verify the research outputs, the original five research questions from chapter 1 will be answered in turn:

- **RQ1: How is innovation currently supported and enabled, or not, to be introduced onto the UK railway?**

The quantitative and qualitative data provided a rich base of evidence to describe the current UK railway innovation landscape. At present, the UK railway introduces innovation when there is clear demand and confidence to proceed – bearing in mind several key issues that were highlighted by the data, which included the structure and fragmentation of the industry, the culture of the industry and resistance to change, the availability of funding, risk aversion, and the alignment of benefits and costs. The research identified Innovate UK funding as a key enabler but that the railway sector is not well-supported in R&D funding for innovation projects, especially compared to the automotive and aerospace sectors.

The role of the UK Government is key in supporting the development and introduction of innovation onto the UK railway, and the current planned reforms are intended to address this and many of the other issues raised by the data.

- **RQ2: What are the critical factors that act as either enablers or blockers to innovation successfully being introduced onto the UK railway?**

The research collected a significant quantity of data using mixed research methods. These sources incorporated an analysis of external and internal factors impacting railway innovation, quantitative data from an online survey, qualitative data from key actor interviews, and further data from a literature review, the use of several relevant case studies, as well as the author's first-hand experience.

The outputs from the research that identified the critical factors is summarised in figure 8.2 (reproduced below).

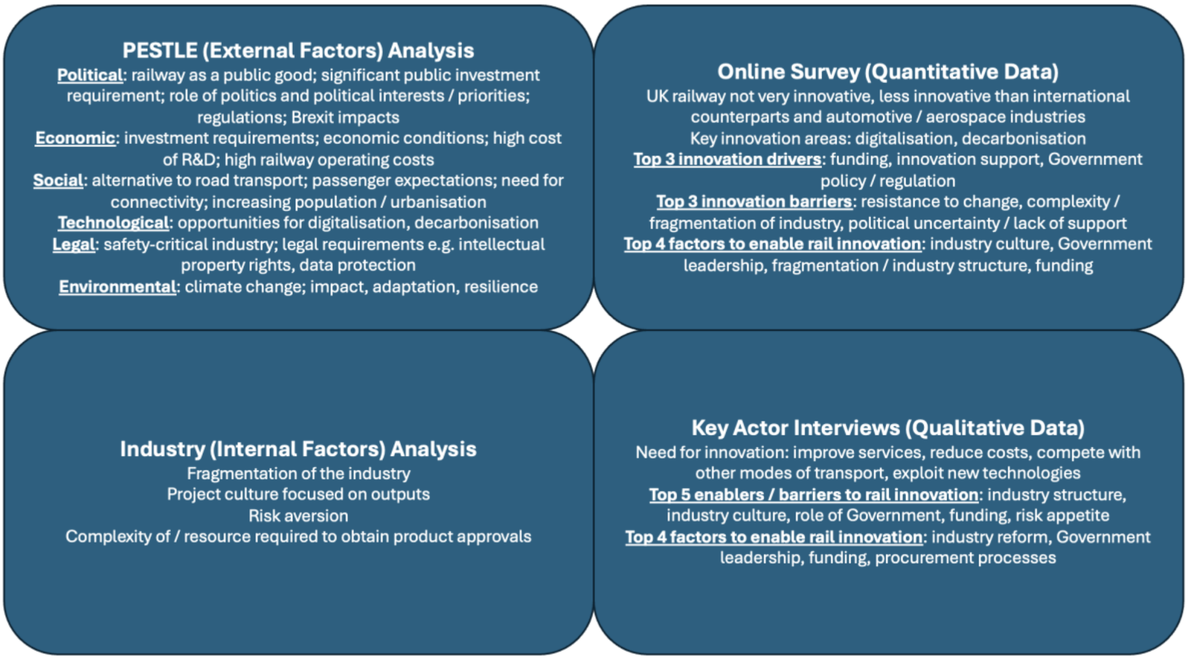

Figure 8.2: High-level summary of findings from research data

Six key factors were identified from the data as being critical in influencing the success of UK railway innovation:

(i) the structure and fragmentation of the UK railway industry
(ii) the culture of the UK railway industry
(iii) the role of the UK Government
(iv) the need for funding
(v) the appetite for risk
(vi) the need for innovation support.

- **RQ3: Who are the key actors involved in UK railway innovation?**

The key actors involved in UK railway innovation were identified in chapter 2 and are summarised in figure 2.5 (reproduced below).

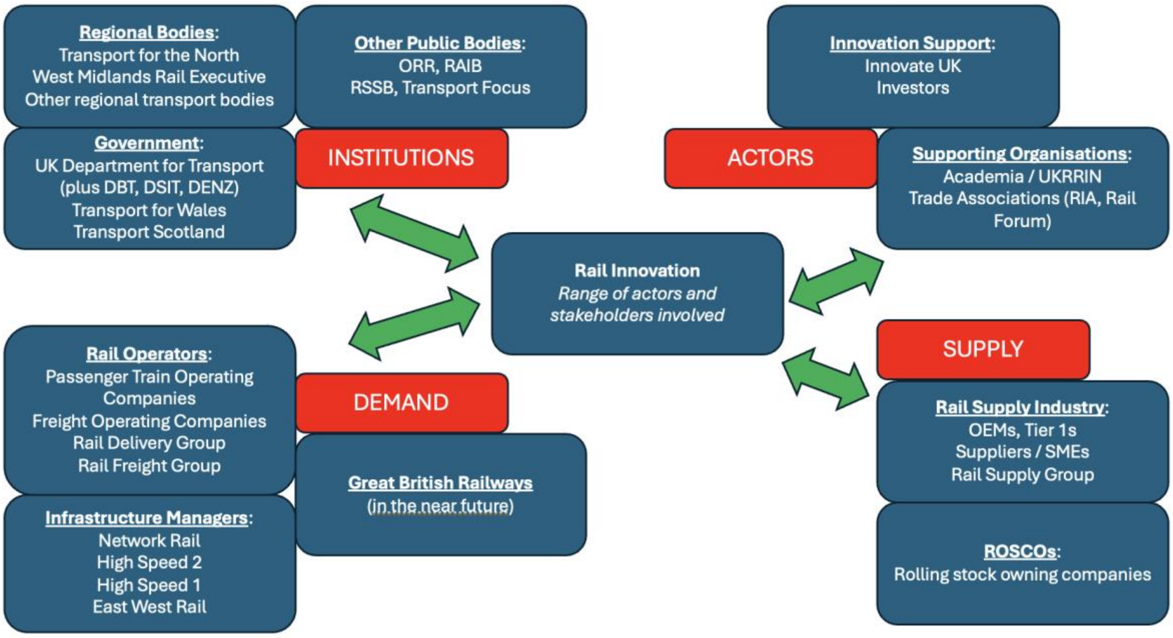

Figure 2.5: Diagram illustrating UK railway innovation landscape actors

- **RQ4: Can we create a model of the UK railway innovation system (recognising that it is a complex system) to understand the factors that drive the success or failure of innovation on the UK railway?**

A model of the UK railway innovation system was developed in chapter 4 and is set out in figure 8.4 (reproduced below). This model used the key learnings from the literature review and the data collection, and observation and analysis, in order to construct as simple a model as is possible to explain a complex system.

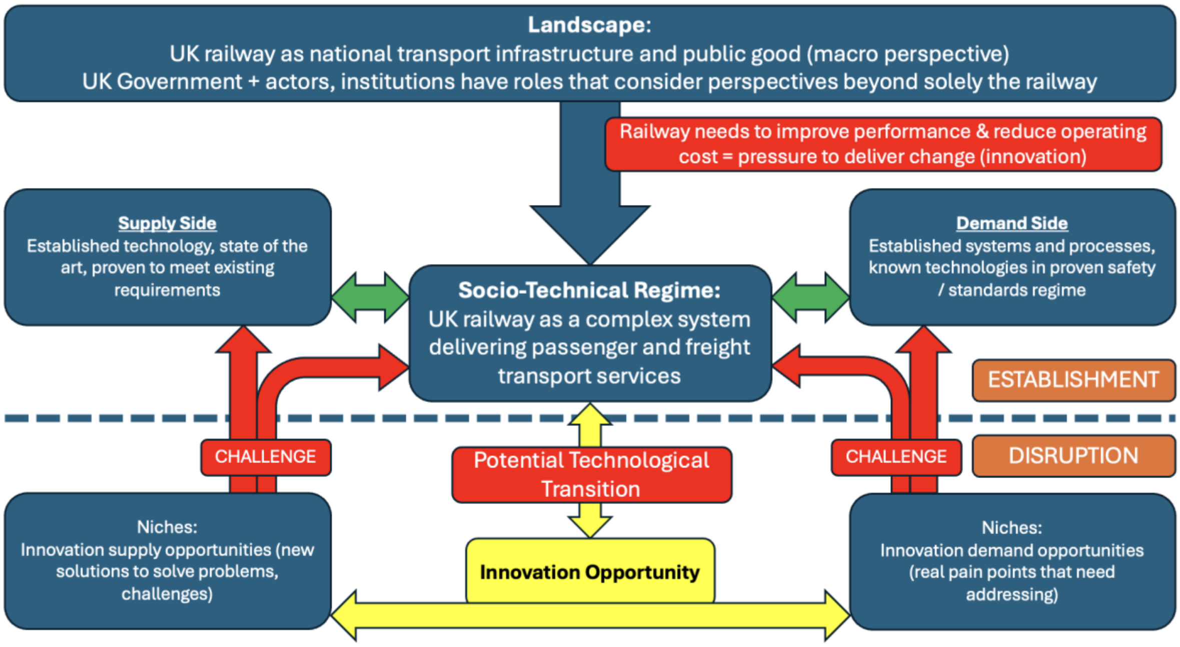

Figure 8.4: Model of the UK railway innovation landscape

- **RQ5: Can we develop a conceptual framework, utilising this model, that can enable the more successful introduction of innovation onto the UK railway?**

Firstly, a conceptual framework of the current UK railway innovation landscape was built from the model (at Figure 9.3 above) to provide a theoretical interpretation of the model, and which could then be adapted to construct the conceptual framework that was the primary objective of this research.

The conceptual framework incorporated the learnings from this research to set out a method for enabling more successful introductions of innovation onto the UK railway in the future – set out in figure 9.4 and reproduced below.

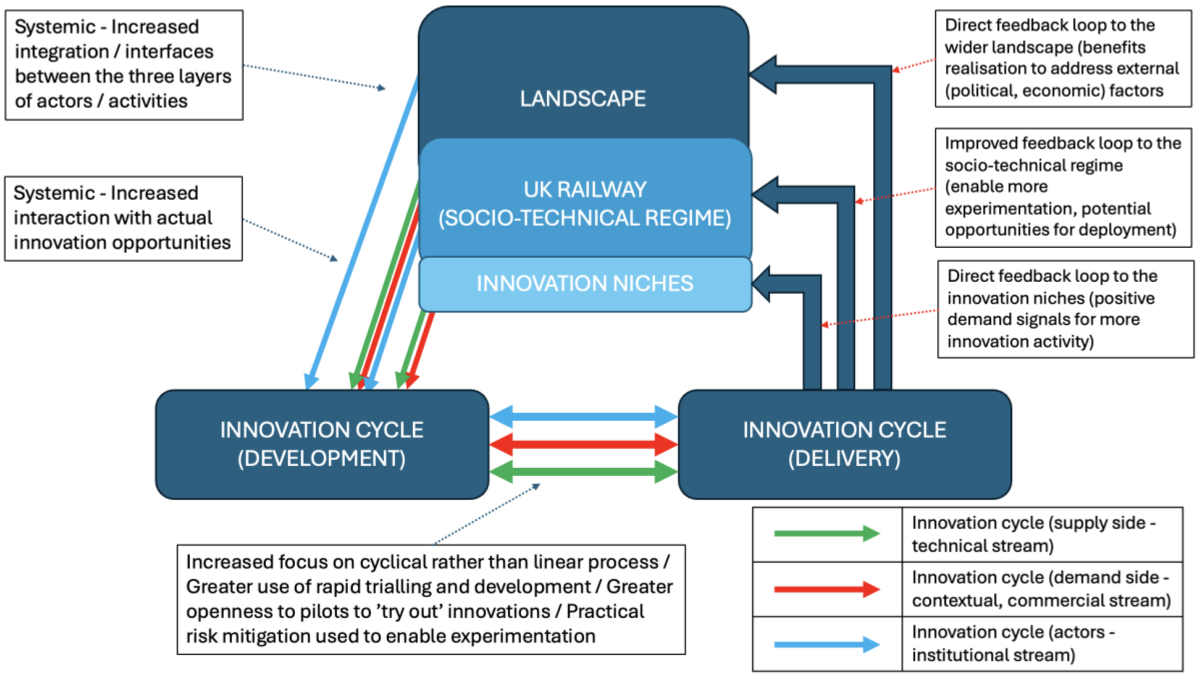

Figure 9.4: The conceptual framework

Reverting back to the hypothesis of this research - the UK railway needs to be more effective in supporting relevant innovation to happen, and to better enable it to be introduced successfully into deployment, in order to meet the expectations of politicians, stakeholders, and the general public, to deliver a railway that provides better services for passengers and freight, and that those improved services are delivered at a lower cost.

In the course of this research, a clear gap in literature on innovation in rail was identified and this research has produced new knowledge to start addressing that gap. This research has shown that there is indeed great demand for innovation to be enabled, and that there is the ability to enable more innovation. The quantitative and qualitative data provides the primary evidence to support the hypothesis.

Furthermore, the model of the UK railway innovation landscape and the conceptual framework developed by this research, could be applied (with some minor editing to reflect the context of the particular railway landscape) to other railways internationally. The fundamental structure of the framework using the 3x3 matrix can be universally applied to railway innovation landscapes – the three temporal phases (landscape, development, delivery), the three system layers (supply industry, the demand side, and the wider actors and institutions), and the three structural dimensions (the landscape, the socio-technical regime, and the niches) are all widely applicable. Future research is planned to dive deeper into the 3x3 matrix, and also to undertake further comparative work to use the 3x3 matrix in international railway contexts.

In the next section, the research sets out the key recommendations drawn from the conceptual framework that can support the railway to enable more innovation.

11.3 Recommendations of this research

Building on the findings from this research, the six critical factors influencing UK railway innovation are used to structure a set of recommendations:

(i) the structure and fragmentation of the UK railway industry

There is a clear need to simplify the structure of the industry and to align the costs and benefits of innovation activity more closely to enable increased opportunity for innovation to support the big picture objectives for the railway i.e. improved performance and reduced operating costs.

Given railway reform is already well under way, the key opportunity is to better understand the scenarios of when innovation should be encouraged, why it should be encouraged, how it should be encouraged, and by whom it should be encouraged as well as for whom. Innovation is seen as a luxury activity outside of the confines of day-to-day operations due to the structural focus on project delivery with a near-term focus.

Recommendation: A long-term strategy and guiding mind for the railway should explicitly state the role and opportunities for innovation as part of the delivery plan for that long-term strategy.

(ii) the culture of the UK railway industry

Resistance to change and a fear of the unknown (in a technology sense) creates a mistrust of trying out new ideas. The safety culture of the railway is not unreasonable, but it should be used pragmatically and not dogmatically. Without an openness to innovation, new technology will still emerge, but the railway will not be prepared for it. Examples of this are the belated awareness of the demand for passenger wifi connectivity or the urgent need for cybersecurity across the railway.

The railway cannot ignore technological developments, therefore having greater awareness of the opportunities and threats at an earlier stage and enabling the industry to prepare for them must be preferable.

Likewise, the standards and approvals regimes are absolutely necessary, but their fundamental objectives – and therefore their application – should be pragmatic and user-friendly, rather than dogmatic and resource-intensive.

Recommendation: culture is learned, and the ambition must be for railway reform to open up greater opportunity for the railway to investigate and consider new ideas and technologies, as well as better assessing and evaluating perceived risk rather than requiring absolute certainty of zero risk. A long-term strategy for the railway must provide clear space for innovation to be valued and utilised as part of the plan to improve the whole system.

(iii) the role of the UK Government

The research findings were absolutely clear that the Government has a critical role in driving the UK railway and has a clear role in leading opportunities to enable (or block) innovation from happening. Firstly, the Government will be the arbiter and controller of railway reform, which will be the critical instrument in the near term for enabling innovation to happen or not. Secondly, the Government controls the availability of public investment - and therefore the consequent attractiveness of private investment - into the railway. Thirdly, public policy will drive the opportunities for investment – the importance of transport decarbonisation, the opportunity to deploy modern digital technologies that improve services for passenger and freight customers, can all be steered by public policy development.

Recommendation: the Government has vast influence on the opportunities available, it can use it positively with greater appreciation of how to design it to strategically support the development of the railway. Rail policy should be designed holistically with both the current railway reform underway, and in tandem with wider policy areas that complement and support rail policy (for example, environmental policy, housing policy, economic policy etc).

(iv) the need for funding

The need for sufficient funding and investment support into research and development, as well as to support innovation projects, was a key and constant output from the research. A lack of long-term certainty over Government support and direction for rail created a loss of appetite to invest in rail, which should be more attractive given the physical and long-term certainty of infrastructure investment.

Recommendation: if public investment is constrained, then the Government should be more proactive in designing policy that can enable private investment to support the ongoing development of the railway.

(v) the appetite for risk

New technology introductions, and introductions in general (i.e. new rolling stock fleets, new signalling systems etc) are frequently beset by delays, often caused by insufficient testing and validation of systems. This has impacted on the appetite for risk where the culture of the industry measures success by near-term project delivery – to time and budget. De-risking projects is incentivised to ensure successful project delivery as the ultimate output and measure of success. This creates a fundamental barrier to innovation.

Recommendation: the industry needs to relearn the opportunities of trying out new ideas. One of the key actors interviewed very strongly advocated the need for funding and support for pilot projects to try out new solutions. This could be gradually scaled up as it made a cultural impact in support of trialling innovation and over how risk is understood, measured, and managed.

(vi) the need for innovation support.

Finally, the importance of innovation support cannot be understated – all the wraparound knowledge and assistance beyond just the provision of funding. The ability to identify where funding might be available through the innovation project cycle, how to access and undertake testing and validation, how to bring the product to market, how to undertake product approvals, where to look for the appropriate standards, who the relevant buyers and competitors are.

Recommendation: good innovation support schemes are vital to enabling innovation to happen and to be successfully introduced onto the UK railway. This should not be left to chance but should be actively supported as part of the effective design of rail policy.

Beyond these initial recommendations, the conceptual framework highlights the importance in the roles of actors and institutions across the three streams of railway innovation – the supply side, the demand side, and the institutional side. Innovation is a far more complex process than an inventor and a buyer, and the innovation system is much more focused on how these wider actors and institutions work together to establish an openness that can enable innovations to be introduced and make a positive difference.

Finally, the research has tested the hypothesis that the UK railway needs to enable more innovation and has proposed a response. In the timescale of this research, it has not been able to test the conceptual framework and put it into practical application to demonstrate its potential efficacy in enabling railway innovation activity. A future hypothesis can suggest that the conceptual framework provides the basis for enabling increased railway innovation and put it to the test by using the framework to test its effectiveness in enabling more innovation activity on the UK railway. So the key recommendation is that the main output from this research – the conceptual framework – is put to use to enable innovation on the railway.

11.4 Limitations of this research and recommendations for future research

The subject of this research is large, but the focus was clearly set by the objective (from chapter 1.5) *"to create a framework of how the UK railway innovation landscape could best be to increase the chances of successful development and deployment, to decrease the risks of unsuccessful innovations being pursued, and to deliver the outcomes being sought for railway innovation (ultimately a better railway)."*

The research has identified six critical factors and used those to build a model and a conceptual framework. The framework could be expanded significantly and used to support the current railway reforms to integrate the role of innovation more effectively within the design of the new system.

Further research could focus on drawing out more quantitative data looking at specific railway innovation projects and their success, the historic use of public funding to support railway innovation projects or looking forwards to design systems of innovation support and optimised funding models for R&D and innovation.

Additional research to dive deeper into the 3x3 matrix to further investigate these layers and their applicability to both other international railway landscapes, and to other industries is envisaged. A key limitation of the research has been the ability to draw out the sheer breadth of potential from the 3x3 matrix and the opportunities it presents to understand railway innovation activity. In addition, there is a future opportunity to complete the feedback loop by undertaking further collection of primary qualitative data to test the proposed 3x3 matrix with key actors.

There would certainly be value in further investigation using both critical and comparative approaches to railway innovation in the UK and other international railways, as well as to other sectors. Such investigations would provide an even richer understanding of the applicability of the matrix in understanding railway innovation and how the framework can support increased innovation activities.

Finally, as discussed in the previous section, the conceptual framework needs to be put into practical use to demonstrate its effectiveness in enabling railway innovation in the UK (and ideally internationally as well). Future research will aim to enable this to take place. It should be envisaged that the framework can enable more effective, and de-risked, innovation activity by embedding the learnings from this research into the planning and delivery of innovation activity. Future research will seek to develop a playbook that allows for the outputs from this work to be put into practical application easily and effectively.

11.5 Contributions of this research to knowledge

At the start of this research, the volume of literature in the field of railway innovation was lower than the author had anticipated. This research has attempted to draw out primary data from industry sources and from a wide range of industry stakeholders, as well as using the author's first-hand experience, to highlight a field of research with much potential for further investigation and many more avenues to explore.

The model of the UK railway innovation landscape, and the conceptual framework, both provide novel structures and analyses of how UK railway innovation happens and how it can be improved upon. Additionally, the six critical factors that can enable UK railway innovation have a firm basis from the volume of quantitative and qualitative data that was collected during this research.

The review of the literature on models and theories of innovation and their application to the UK railway sector provides a new insight and understanding and provided a structure to the building of the model and the conceptual framework.

The quantitative and qualitative data collected during the course of this research from the online survey and the key actor interviews provide a breadth of valuable insights into the UK railway innovation landscape and provide a number of opportunities for further investigation as well as informing this research project.

Taken all together, the findings from the research provide a framework and a new methodology for investigating and comprehending railway innovation and can be used to inform not just future research but also actual railway reform and practice.

11.6 Final comments

The author has used this research project to inform practice in their professional work, as well as using their significant experience in the field to inform this research. The UK railway is a vitally important part of our national transport infrastructure and critical element within the social, economic, and environmental spheres of the nation, supporting our health, wealth, and wellbeing.

The railway needs to accept innovation as being a necessary part of operation and integrate it more fully into business as usual. To do that, there needs to be a greater appreciation of the tangible benefits that can be delivered by innovation, as well as real and demonstrable support that the industry wants to achieve these.

A number of key actors interviewed expressed their desire to see more innovation but scepticism that it could be a widepsread ambition, recognising that the railway industry is inherently conservative and insular – the vast majority of people interviewed and surveyed (43 and 202 respectively) all considered innovation necessary to improve and develop the UK railway, but that it would be a huge challenge to make real progress any time soon. This indicates the challenge is as much cultural and personal, as it is structural and political. The research has tested the hypothesis that the UK railway could and should attempt to enable more innovation to succeed on the railway, and the ambition for the conceptual framework that has been developed is to help address that need – let us hope that it can be done.

List of References

Acciarini, C., et al. (2022). "Can digitalization favour the emergence of innovative and sustainable business models? A qualitative exploration in the automotive sector." Journal of Strategy and Management 15(3): 335-352.

Adams, E. (2016). "All abroad: why UK rail engineers are valued overseas." Retrieved 11 November 2024, from https://www.theengineer.co.uk/content/in-depth/all-abroad-why-uk-rail-engineers-are-valued-overseas/.

Advanced Propulsion Centre (2024). "About Us." Retrieved 11 November 2024, from https://www.apcuk.co.uk/about/

Advanced Propulsion Centre (2024). "Automotive Transformation Fund." Retrieved 11 November 2024, from https://www.apcuk.co.uk/get-involved/funding/automotive-transformation-fund/

Aldcroft, D. H. (1969). "Innovation on the Railways: The Lag in Diesel and Electric Traction." Journal of Transport Economics and Policy 3(1): 96-107.

Alhassan, Y. A. (2024). "Social Capital and Information Flow in Decision Making: A Social Network Analysis of Actors in a Road Expansion Project in Kristiansand, Norway." International Journal of Politics, Culture, and Society.

Almalki, S. (2016). "Integrating Quantitative and Qualitative Data in Mixed Methods Research—Challenges and Benefits." Journal of Education and Learning 5(3): 288.

Alstom (2016). Alstom unveils its zero-emission train Coradia iLint at InnoTrans.

Alstom (2024). "Alstom Coradia iLint – the world's 1st hydrogen powered passenger train." Retrieved 22 January 2025, from https://www.alstom.com/solutions/rolling-stock/alstom-coradia-ilint-worlds-1st-hydrogen-powered-passenger-train

Álvarez-Sanjaime, Ó., et al. (2013). "Competition and horizontal integration in maritime freight transport." Transportation Research Part E: Logistics and Transportation Review 51: 67-81.

Anciaes, P. and K. A. J. Alhassan (2024). Economic and social impacts of public transport investments: A scoping literature review. Advances in Transport Policy and Planning: 227-254.

Association, I. A. T. (2024). "Fly Net Zero." Retrieved 21 January 2025, from https://www.iata.org/en/programs/sustainability/flynetzero/

Atkins Transportation (2015). Journeys of the Future.

Ayres, R. U. (1990). "Technological Transformations and Long Waves Part 1." TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE 37: 1-37.

Bagwell, P. (2004). "The Sad State of British Railways." The Journal of Transport History 25(2): 111-124.

Barroso, G. D., et al. (2022). "Electrified Automotive Propulsion Systems: State-of-the-Art Review." IEEE Transactions on Transportation Electrification 8(2): 2898-2914.

Baumann, J. (2023). "Shifting to Sustainable Shipping: Actors and Power Shifts in Shipping Emissions in the IMO." Sustainability 15(17).

BBC (2019). "All aboard Britain's first hydrogen train." Retrieved 22 January 2025, from https://www.bbc.co.uk/news/business-48698532

BBC News (2021). "Severn Valley Railway helps to convert hydrogen engine." Retrieved 22 January 2025, from https://www.bbc.co.uk/news/uk-england-hereford-worcester-56859594

Bergek, A., et al. (2008). "Analyzing the functional dynamics of technological innovation systems: A scheme of analysis." Research Policy 37(3): 407-429.

Berger, P. L. and T. Luckmann (1966). The Social Construction of Reality - A Treatise in the Sociology of Knowledge. New York, Anchor.

Berkhout, A. J., et al. (2006). "Innovating the innovation process." International Journal of Technology Management 34(3/4): 390.

Bešinović, N. (2020). "Resilience in railway transport systems: a literature review and research agenda." Transport Reviews 40(4): 457-478.

Bhattacharyya, K. S. (2015). "Smarter–lighter–greener: research innovations for the automotive sector." Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 471(2179): 20140938.

Biogradlija, A. (2021). University of Birmingham hydrogen technology showcased at COP26 United Nations Climate Change Summit. Energy News Biz.

Bogers, M., et al. (2018). "Open Innovation: Research, Practices, and Policies." California Management Review 60(2): 5-16.

Bogue, R. (2022). "The changing face of the automotive robotics industry." Industrial Robot: the international journal of robotics research and application 49(3): 386-390.

Bowling, A. and E. Shah, Eds. (2005). Handbook of Health Research Methods: Investigation, Measurement and Analysis, Open University Press.

Bravo, A., et al. (2022). "Emissions of future conventional aircrafts adopting evolutionary technologies." Journal of Cleaner Production 347: 131246.

Burrows, A., et al. (2022). Introducing the Birmingham Rail Innovation Process: a framework for unlocking innovation in the rail sector. World Congress of Railway Research. Birmingham, RSSB.

Caliari, T., et al. (2023). "Global value chains and sectoral innovation systems: An analysis of the aerospace industry." Structural Change and Economic Dynamics 65: 36-48.

Calvert, C., et al. (2021). "Concept development and testing of the UK's first hydrogen-hybrid train (HydroFLEX)." Railway Engineering Science 29(3): 248-257.

Carlsson, B. and R. Stankiewicz (1991). "On the nature, function and composition of technological systems." Journal of Evolutionary Economics 1(2): 93-118.

Casson, M. (2009). The World's First Railway System - Enterprise, Competition and Regulation on the Railway Network in Victorian Britain. Oxford, Oxford University Press.

Chandarana, A. (2023). "Great British Railways: the great enabler for rail innovation." https://gbrtt.co.uk/keep-informed/blogs/enabler-for-rail-innovation/.

Chesbrough, H. and M. Bogers (2014). Explicating Open Innovation: Clarifying an Emerging Paradigm for Understanding Innovation. New Frontiers in Open Innovation. H. Chesbrough, W. Vanhaverbeke and J. West. Oxford, Oxford University Press.

Chesbrough, H., et al. (2018). "Value Creation and Value Capture in Open Innovation." Journal of Product Innovation Management 35(6): 930-938.

Chesbrough, H. W. (2003). Open Innovation: The New Imperative for Creating and Profiting from Technology, Harvard Business Press.

Chesbrough, H. W. and S. Brunswicker (2013). Managing open innovation in large firms, University of California, Berkeley Fraunhofer Society.

Chiltern Railways (2022). "Chiltern Railways puts Britain's first hybrid-powered train to the test." Retrieved 22 January 2025, from https://www.chilternrailways.co.uk/news/chiltern-tests-britains-first-hybrid-powered-train

Chiltern Railways (2023). Chiltern Railways on track for a greener future with vegetable oil powered trains.

Christodoulou, A. and K. Cullinane (2019). "Identifying the Main Opportunities and Challenges from the Implementation of a Port Energy Management System: A SWOT/PESTLE Analysis." Sustainability 11(21): 6046.

Clark, J., et al. (1981). "Long waves, inventions, and innovations." Futures 13(4): 308-322.

Clinnick, R. (2015). Batteries Included. RAIL Magazine.

Commission, European (2018). Final report of the High-Level Panel of the European Decarbonisation Pathways Initiative.

Commission, European (2021). Europe's Rail Joint Undertaking Master Plan, European Commission.

Committee, Public Accounts (2024). HS2 verdict: Scheme now very poor value for money after Northern leg cancellation. UK Parliament, UK Parliament.

Conrad, C. F. and R. C. Serlin, Eds. (2011). The SAGE Handbook for Research in Education - Pursuing ideas as the keystone of exemplary inquiry (2nd edition). Los Angeles, SAGE.

Cox, S. E. (1957). "Approach to Modernisation." Journal of the Institution of Locomotive Engineers 47(258): 384-416.

Crampton, R. (2024). Transforming rail freight with hydrogen: Vanguard STS and the HydroShunter. Rail Business Daily, RBD.

Davies, K. (2024). UKRI / Innovate UK Rail Innovation Program & Rail Innovation in the Context of Infrastructure.

Degiuli, N., et al. (2021). "The impact of slow steaming on reducing CO2 emissions in the Mediterranean Sea." Energy Reports 7: 8131-8141.

Dicicco-Bloom, B. and F. B. Crabtree (2006). "The qualitative research interview." Medical Education 40(4): 314-321.

Diercks, G., et al. (2019). "Transformative innovation policy: Addressing variety in an emerging policy paradigm." Research Policy 48(4): 880-894.

Divall, C. (2006). "Technological networks and industrial research in Britain: The London, Midland & Scottish Railway, 1926–47." Business History 48(1): 43-68.

Dobell, M. (2017). RRUKA Annual Conference 2017. Rail Engineer.

Economics, Oxford (2021). The economic contribution of UK rail.

Ende, D. V. J. and R. Kemp (1999). "Technological transformations in history: how the computer regime grew out of existing computing regimes." Research Policy 28(8): 833-851.

Enkel, E., et al. (2009). "Open R&D and open innovation: exploring the phenomenon." R&D Management 39(4): 311-316.

Europe, Council of (2021). Council commits to nine institutionalised European partnerships.

Europes Rail Joint Undertaking (2024). Europe's Rail Joint Undertaking Multi-Annual Work Programme.

Eurostat, O. (2005). Oslo Manual: Guidelines for collecting and interpreting innovation data (Third edition).

Fch2Rail (2024). "FCH2Rail Project - Fuel Cell Hybrid PowerPack for Rail Applications." Retrieved 22 January 2025, from https://fch2rail.eu.

Fernando, A. (2018). STRATEGIES TO PERFORM A MIXED METHODS STUDY.

Finger, M. and J. Montero (2020). Handbook on Railway Regulation.

Fowler, F. J. and C. Cosenza (2012). The SAGE Handbook of Applied Social Research Methods (2nd ed.). L. Bickman and D. Rog. Los Angeles, SAGE.

Franco-Trigo, L., et al. (2020). "Stakeholder analysis in health innovation planning processes: A systematic scoping review." Health Policy 124(10): 1083-1099.

Freeman, C. (1991). "Innovation, Changes of Techno-Economic Paradigm and Biological Analogies in Economics." Revue économique 42(2): 211.

Freeman, C. (2019). "History, Co-Evolution and Economic Growth." Industrial and Corporate Change 28(1): 1-44.

Gall, M. D., et al. (2003). Educational Research: An Introduction, 7th ed. Boston, Pearson.

Garcia, R., et al. (2019). "Challenges of creating and capturing value in open eco-innovation: Evidence from the maritime industry in Denmark." Journal of Cleaner Production 220: 642-654.

Geels, W. F. (2002). "Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study." Research Policy 31(8-9): 1257-1274.

Geels, W. F. (2004). "From sectoral systems of innovation to socio-technical systems." Research Policy 33(6-7): 897-920.

Geels, W. F. (2010). "Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective." Research Policy 39(4): 495-510.

Geels, W. F. (2011). "The multi-level perspective on sustainability transitions: Responses to seven criticisms." Environmental Innovation and Societal Transitions 1(1): 24-40.

Geels, W. F. (2012). "A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies." Journal of Transport Geography 24: 471-482.

Geels, W. F. (2018). "Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective." Energy Research & Social Science 37: 224-231.

Gerring, J. (2017). "Qualitative Methods." Annual Review of Political Science 20(1): 15-36.

Gilchrist, A. (2009). "A history of engineering research on British Railways." Institute of Railway Studies and Transport History Working papers in railway studies, number 10.

Gössling, S., et al. (2021). "A global review of marine air pollution policies, their scope and effectiveness." Ocean & Coastal Management 212: 105824.

Great British Railways Transition Team (2025). "GBRTT: About Us." Retrieved 22 January 2025, from https://gbrtt.co.uk/about-us/

Green Business Journal (2021). "COP26 showcase for hydrogen train." Retrieved 22 January 2025, from https://greenbusinessjournal.co.uk/cop26-showcase-for-hydrogen-train/

Haigh, L. (2024). Oral Statement to Parliament: Our progress in overhauling the railways. D. f. Transport, UK Government.

Harrisson, D. and M. Laberge (2002). "Innovation, Identities and Resistance: The Social Construction of An Innovation Network." Journal of Management Studies 39(4): 497-521.

Harwood, Stephenson (2024). https://www.shlegal.com/insights/what-is-the-future-for-rail-operating-contracts

Hekkert, P. M., et al. (2020). "Mission-oriented innovation systems." Environmental Innovation and Societal Transitions 34: 76-79.

Hesse-Biber, S. (2010). "Qualitative Approaches to Mixed Methods Practice." Qualitative Inquiry 16(6): 455-468.

Hillmansen, S. (2003). "The application of fuel cell technology to rail transport operations." Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 217(4): 291-298.

Hirschlag, A. (2020). Next stop, hydrogen-powered trains. BBC Future Planet.

Hospers, G.-J. (2005). "Joseph Schumpeter and his legacy in innovation studies." Knowledge, Technology & Policy 18(3): 20-37.

How, A. (2003). Critical Theory. London, Palgrave Macmillan.

Hughes, T. P. (2004). Human-built world: how to think about technology and culture. Chicago, University of Chicago Press.

Hunt, S. (2023). Disappointment as Chiltern Railways scraps hybrid train plans. London Evening Standard.

Innovation, UK Research and (2020). "HydroFLEX Mainline Testing." Retrieved 22 January 2025, from https://gtr.ukri.org/projects?ref=971658.

Institution of Civil Engineers (2025). "Stockton and Darlington Railway." Retrieved 20 January 2025, from https://www.ice.org.uk/what-is-civil-engineering/infrastructure-projects/stockton-and-darlington-railway

Institution of Civil Engineers (2025). "Liverpool and Manchester Railway." Retrieved 20 January 2025, from https://www.ice.org.uk/what-is-civil-engineering/infrastructure-projects/liverpool-and-manchester-railway#:~:text=The%20L%26MR%20was%20the%20first,the%20cloth%20mills%20of%20Manchester

International Council on Systems Engineering (2015). Systems Engineering Jr. Handbook, INCOSE.

International Council on Systems Engineering (2025). "About Systems Engineering / Physical and Conceptual Definitions." Retrieved 19 January 2025, from https://www.incose.org/about-systems-engineering/system-and-se-definitions/physical-and-conceptual

International Maritime Organisation (2023). "2023 IMO Strategy on Reduction of GHG Emissions from Ships." Retrieved 11 November 2024, from https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

Ivankova, V. N., et al. (2006). "Using Mixed-Methods Sequential Explanatory Design: From Theory to Practice." Field Methods 18(1): 3-20.

Janssen, J. M., et al. (2021). "The promises and premises of mission-oriented innovation policy—A reflection and ways forward." Science and Public Policy.

Kelley-Quon, I. L. (2018). "Surveys: Merging qualitative and quantitative research methods." Seminars in Pediatric Surgery 27(6): 361-366.

Kemp, R. (1994). "Technology and the transition to environmental sustainability." Futures 26(10): 1023-1046.

Kessel, C. (2023). Signalling investment: the next six years. Rail Engineer.

Kirchherr, J., et al. (2023). "Missions and mission-oriented innovation policy for sustainability: A review and critical reflection." Environmental Innovation and Societal Transitions 47: 100721.

Kleinknecht, A. and B. Verspagen (1990). "Demand and innovation: Schmookler re-examined." Research Policy 19(4): 387-394.

Koncar (2022). "Battery electric multiple unit (BEMU) prototype and battery multiple unit prototype (BMU) with 6 energy storage devices delivered to HŽ Passenger Transport." Retrieved 22 January 2025, from https://www.koncar.hr/en/kev/projects/battery-electric-multiple-unit-bemu-prototype-and-battery-multiple-unit-prototype-bmu.

Laursen, K. and A. Salter (2006). "Open for innovation: the role of openness in explaining innovation performance among U.K. manufacturing firms." Strategic Management Journal 27(2): 131-150.

Eurolex, EU (2024). "Joint Undertakings." Retrieved 22 January 2025, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:joint_undertaking

Li, L., et al. (2022). "Digital Twin in Aerospace Industry: A Gentle Introduction." IEEE Access 10: 9543-9562.

Link, Marine (2025). "Digitalization and Smart Shipping: Transforming the Maritime Industry." Retrieved 21 January 2025, from https://www.marinelink.com/articles/maritime/digitalization-and-smart-shipping-transforming-the-maritime-101642

Lundvall, B.-A. (1992). National Systems of Innovation: Toward a theory of innovation and active learning. London, Anthem Press.

Lundvall, B.-A. k. (2016). The Learning Economy and the Economics of Hope. London, Anthem Press.

Lydall, R. (2023). UK first as trains running on vegetable oil use Marylebone station. London Evening Standard.

Malerba, F. (2002). "Sectoral systems of innovation and production." Research Policy 31(2): 247-264.

Mallouppas, G. and A. E. Yfantis (2021). "Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals." Journal of Marine Science and Engineering 9(4): 415.

Marinova, D. and J. Phillimore (2003). Models of Innovation. The International Handbook on Innovation. L. V. Shavinina, Elsevier.

Markard, J. and B. Truffer (2008). "Technological innovation systems and the multi-level perspective: Towards an integrated framework." Research Policy 37(4): 596-615.

Mazzucato, M. (2018). "Mission-oriented innovation policies: challenges and opportunities." Industrial and Corporate Change 27(5): 803-815.

Meissner, D. and M. Kotsemir (2016). "Conceptualizing the innovation process towards the 'active innovation paradigm'—trends and outlook." Journal of Innovation and Entrepreneurship 5(1).

Modern Railways (2021). New HydroFLEX debuts at COP. Modern Railways.

Modern Railways (2022). Hybrid 165 Progress. Modern Railways.

Morrows, R. A. (1994). Critical Theory and Methodology. Los Angeles, SAGE.

Müller, K. A., et al. (2012). "Comparing project management practices in new product development: a study in the automotive, aerospace and rail transport industry." International Journal of Project Organisation and Management 4(3): 203.

Nash, C., et al. (2020). "The impact of rail industry restructuring on incentives to adopt innovation: A case study of Britain." Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 234(3): 331-337.

Nelson, R. R. (2000). National Innovation Systems. Regional Innovation, Knowledge and Global Change. Z. J. Acs, Routledge.

Nelson, R. R. (2005). Technology, Institutions and Economic Growth, Harvard University Press.

Nelson, R. R. and G. S. Winter (1977). "In search of useful theory of innovation." Research Policy 6(1): 36-76.

Nemoto, T. and D. Beggar (2013). Developing Likert-Scale Questionnaires. JALT 2013.

Network Rail (2020). Traction Decarbonisation Network Strategy.

Network Rail (2024). "A summary of our CP7 delivery plan 1 April 2024 to 31 March 2029." Retrieved 11 November 2024, from https://www.networkrail.co.uk/wp-content/uploads/2024/05/Network-Rail-CP7-Delivery-Summary.pdf

Nobelius, D. (2004). "Towards the sixth generation of R&D management." International Journal of Project Management 22(5): 369-375.

Odlyzko, A. (2010). "Collective Hallucinations and Inefficient Markets: The British Railway Mania of the 1840s." SSRN Electronic Journal.

OECD (2008). Competition, Patents and Innovation: Key findings, summary and notes. Series Roundtables on Competition Policy No.72. Paris, OECD.

OECD (2023). How the green and digital transitions are reshaping the automotive ecosystem. OECD Science, Technology and Industry Policy Papers.

Organisation, I. C. A. (2024). "CORSIA." Retrieved 21 January 2025, from https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

Ott, R. L. and M. Longnecker (2010). An Introduction to Statistical Methods and Data Analysis, Brooks/Cole.

Padam, S. (1998). "Transport needs regulation." Current Science 75(8): 790-794.

Partnership, Clean Hydrogen (2024). "Clean Hydrogen Partnership." Retrieved 22 January 2025, from https://www.clean-hydrogen.europa.eu/index_en

Pereira, A. B., et al. (2022). "Technology trajectory in aviation: Innovations leading to value creation (2000–2019)." International Journal of Innovation Studies 6(3): 128-141.

Perunovic, Z. and J. Vidic-Perunovic (2011). Innovation in the Maritime Industry. 22nd POMS Annual Conference, Reno, Nevada USA.

Pinch, J. T. and E. W. Bijker (1984). "The Social Construction of Facts and Artefacts: or How the Sociology of Science and the Sociology of Technology might Benefit Each Other." Social Studies of Science 14(3): 399-441.

Podmetina, D., et al. (2018). "Developing a competency model for open innovation." Management Decision 56(6): 1306-1335.

Porter, E. M. (1996). "Competitive Advantage, Agglomeration Economies, and Regional Policy." International Regional Science Review 19(1-2): 85-90.

Porter, M. E. (1998). "Clusters and Competition - New agendas for Companies, Governments, and Institutions." On Competition 7.

Qu, Q. S. and J. Dumay (2011). "The qualitative research interview." Qualitative Research in Accounting & Management 8(3): 238-264.

Rail Business (2023). HVO fuel switch starts Chiltern Railways decarbonisation drive. Rail Business UK.

Rail Business (2025). HydroShunter demonstrator loco unveiled at Severn Valley Railway. Rail Business UK.

Rail Supply Group (2016). Fast Track to the Future.

Railway 200 (2024). "Railway 200." Retrieved 11 November 2024, from https://railway200.co.uk

Railway Gazette International (2018). Thameslink first with ATO over ETCS. Railway Gazette International.

Railway Gazette International (2024). Croatian KONČAR Group among the first in Europe to manufacture Battery Multiple Unit and the only one to present such an advancement at InnoTrans 2024. Railway Gazette International, Railway Gazette International.

Railway Industry Association (RIA) (2022). A Railway Innovation Strategy.

Railway Industry Association (RIA) (2024). "Network Rail's R&D Portfolio." 16 January 2025.

Raza, Z., et al. (2023). "Digital transformation of maritime logistics: Exploring trends in the liner shipping segment." Computers in Industry 145: 103811.

Records, Guinness Book of World (2025). "First public electric railway." Retrieved 20 January 2025, from https://www.guinnessworldrecords.com/world-records/first-public-electric-railway.

Rip, A. and R. Kemp (1998). Technological Change. Human Choice and Climate Change, Battle Press. 2: Resources and Technology: 327-399.

Road, Office of Rail and (2023). Rail Industry Finance (UK), ORR.

Road, Office of Rail and (2024). Table 1220 - Passenger journeys.

Road, Office of Rail and (2024). "Getting value for money on the £67bn spent on Britain's railway infrastructure." Retrieved 16 January 2025, from https://www.orr.gov.uk/search-news/getting-value-money-ps67bn-spent-britains-railway-infrastructure#:~:text=In%20the%20five%20years%20between,rail%20infrastructure%20in%20Great%20Britain

Road, Office of Rail and (2024). Rail Infrastructure and Assets 2024. ORR Data Portal, ORR.

Rogelberg, S. G., Ed. (2004). Handbook of Research Methods in Industrial and Organisational Psychology. Oxford, Blackwell.

Rogge, S. K. and N. Goedeking (2024). "Challenges in accelerating net-zero transitions: insights from transport electrification in Germany and California." Environmental Research Letters 19(4): 044007.

Rothwell, R. (1994). "Towards the Fifth-generation Innovation Process." International Marketing Review 11(1): 7-31.

Schmookler, J. (1962). "Economic Sources of Inventive Activity." The Journal of Economic History 22(1): 1-20.

Schumpeter, A. J. (2013). Capitalism, Socialism and Democracy.

Shahriar, F. M. and A. Khanal (2022). "The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF)." Fuel 325: 124905.

Shahzad, K. and I. I. Cheema (2024). "Low-carbon technologies in automotive industry and decarbonizing transport." Journal of Power Sources 591: 233888.

Shift2Rail (2019). "Shift2Rail factsheet." Retrieved 21 January 2025, from https://rail-research.europa.eu/wp-content/uploads/2018/12/Shift2Rail-Factsheet-LATEST-VERSION.pdf

Smith, R. (1997). The Advanced Railway Research Centre - Growth and Progress. World Congress on Railway Research. Firenze, Italy.

Stacy, M. (2015). Batteries Included. Rail Engineer.

Steele, H. and C. Roberts (2022). Towards a Sustainable Digital Railway. Sustainable Railway Engineering and Operations: 239-263.

Stephen, P. (2021). UPDATED: Freightliner to withdraw entire electric fleet. RAIL Magazine, Bauer Consumer Media Ltd.

Stoycheva, S., et al. (2018). "Multi-criteria decision analysis framework for sustainable manufacturing in automotive industry." Journal of Cleaner Production 187: 257-272.

Strategy, Department for Business Energy and Industrial (2018). UK Government Industrial Strategy: Rail Sector Deal. Beis, HM Government.

Swanson, R. A. and E. F. H. Iii, Eds. (2005). Research in Organizations - Foundations and Methods of Inquiry. San Francisco, Barrett Koehler.

Sweetman, D., et al. (2010). "Use of the Transformative Framework in Mixed Methods Studies." Qualitative Inquiry 16(6): 441-454.

Taherdoost, H. (2016). "Sampling Methods in Research Methodology; How to Choose a Sampling Technique for Research." International Journal of Academic Research in Management (IJARM) 5.

Taherdoost, H. (2022). "How to Conduct an Effective Interview; A Guide to Interview Design in Research Study." 11(1): 39-51.

Tashakkori, A. and C. Teddlie, Eds. (2003). Handbook of Mixed Methods in Social & Behavioural Research, SAGE.

Technology, Rail (2015). Independently Powered Electric Multiple Unit (IPEMU), Essex. Rail Technology Magazine.

Thompson, R. W. (1990). "Long waves, technological innovation, and relative decline." International Organization 44(2): 201-233.

Tijan, E., et al. (2021). "Digital transformation in the maritime transport sector." TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE 170: 120879.

Tolmie, A., et al., Eds. (2011). Quantitative Methods in Educational and Social Research using SPSS, McGraw Hill Education.

Tom, L., et al. (2021). "Commercial Aircraft Electrification—Current State and Future Scope." Energies 14(24): 8381.

Transport, Department for (2011). Realising the potential of rail in Great Britain. DfT. London, UK Government.

Transport, Department for (2012). Reforming our Railways: Putting the Customer First. DfT. London, UK Government.

Transport, Department for (2016). Rail Reform: The Shaw Report. DfT. London, UK Government.

Transport, Department for (2019). The Williams Rail Review. DfT. London, UK Government.

Transport, Department for (2021). Great British Railways: Williams-Shapps plan for rail. DfT. London, UK Government.

Transport, Department for (2021). Transport Decarbonisation Plan - Decarbonising transport: a better, greener Britain. DfT. London, UK Government.

Transport, Department for (2024). DfT Annual Report and Accounts. DfT. London, UK Government.

Transport, Department for (2021). Great British Railways: The Williams-Shapps Plan for Rail. DfT. London, UK Government.

Treasury, H. M. (2024). Fixing the foundations: public spending audit 2024-25. H. M. Treasury. London, UK Government.

UK Rail Research and Innovation Network (UKRRIN) (2025). "UKRRIN." Retrieved 20 January 2025, from https://www.ukrrin.org.uk

UK Rail Research and Innovation Network (UKRRIN) (2019). "The UK's first hydrogen train makes its debut at Rail Live 2019." Retrieved 22 January 2025, from https://www.ukrrin.org.uk/the-uks-first-hydrogen-train-makes-its-debut-at-rail-live-2019/

UK Rail Research and Innovation Network (UKRRIN) (2020). "HydroFLEX Update: The world's first bi-mode electric train moves closer to commercialisation." Retrieved 22 January 2025, from https://www.ukrrin.org.uk/hydroflex-update-the-worlds-first-bi-mode-electric-train-moves-closer-to-commercialisation/

Unger, R. M. (1983). "The Critical Legal Studies Movement." Harvard Law Review 96(3): 561-675.

Unger, R. M. (2015). The Critical Legal Studies Movement - Another Time, a Greater Task. London, Verso.

University of Birmingham (2018). University of Birmingham signs joint initiative to develop HydroFlex – the UK's first hydrogen train.

Vanguard Sustainable Transport Solutions (2024). "The UK’s first hydrogen powered freight locomotive." Retrieved 22 January 2025, from https://vanguardsts.com/uks-first-hydrogen-powered-freight-locomotive/

Vasco, C. J. (2021). Additive manufacturing for the automotive industry. Additive Manufacturing: 505-530.

Vickers, L. R. (1999). "The Beginnings of Diesel Electric Traction." Transactions of the Newcomen Society 71(1): 115-127.

Volks Railway (2025). "History of Volks Railway." Retrieved 20 January 2025, from https://volksrailway.org.uk/history/

Wang, T., et al. (2023). "Green development of the maritime industry: Overview, perspectives, and future research opportunities." Transportation Research Part E: Logistics and Transportation Review 179: 103322.

Watson, R. (2015). "Quantitative research." Nursing Standard 29(31): 44-48.

Weber, M. K. and H. Rohracher (2012). "Legitimizing research, technology and innovation policies for transformative change." Research Policy 41(6): 1037-1047.

Weng, L.-J. (2004). "Impact of the Number of Response Categories and Anchor Labels on Coefficient Alpha and Test-Retest Reliability." Educational and Psychological Measurement 64(6): 956-972.

West Midlands Trains (2023). West Midlands Trains Decarbonisation Strategy.

Winnett, J., et al. (2017). Automotive to rail : can technologies cross the gap? IMechE Stephenson Conference: Research for Railways, London, University of Warwick.

Wiseman, Y. (2019). "Driverless Cars Will Make Passenger Rail Obsolete." Retrieved 11 November2024, from https://technologyandsociety.org/driverless-cars-will-make-passenger-rail-obsolete/

Zhu, L., et al. (2018). "Light-weighting in aerospace component and system design." Propulsion and Power Research 7(2): 103-119.

Zisi, V., et al. (2021). "The impact of the 2020 global sulfur cap on maritime CO2 emissions." Maritime Business Review 6(4): 339-357.