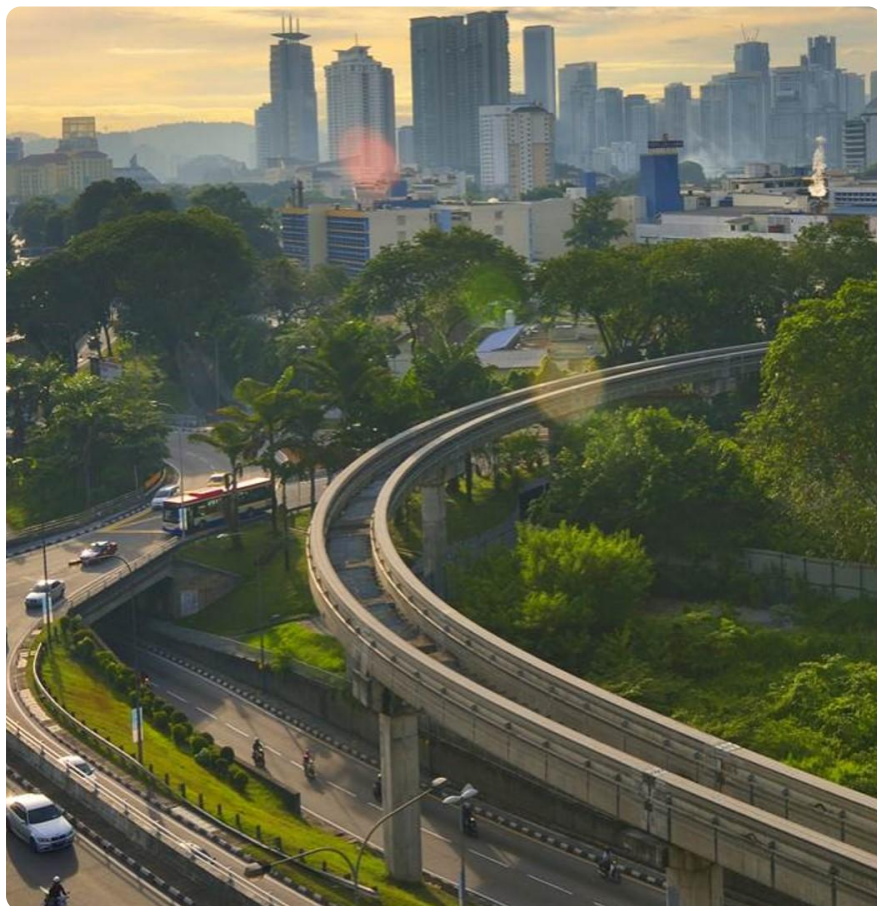




Economic Appraisal of Resilience in Transport

Literature Review, Conceptual Framework
and TAG Recommendations

March 2026 – Final

Bringing Ingenuity to Life

paconsulting.com

Corporate Headquarters

10 Bressenden Place
London
SW1E 5DN
+44 20 7730 9000

paconsulting.com

**Prepared by: Caroline Field, Robert Vaughan,
Johanna Tewolde, Benjamin Wratten**

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Plain English Summary for policy makers

Why this work matters

Transport in the UK is facing disruptions that are becoming more frequent, severe and interconnected. These shocks range from storms, cyber incidents, and major accidents to long term stresses such as climate change, ageing assets, and workforce gaps. Disruption often cascades across sectors like energy, water, and digital, which raises the stakes for decision making. At present, there is no consistent way in TAG to appraise the resilience benefits of transport schemes. This work reviews the evidence and proposes a framework to fill that gap.

What the evidence says

- The review covered more than 200 sources across academia, government, and grey literature in the UK and internationally. Resilience is multi-dimensional. It means anticipating risks, withstanding shocks, recovering quickly, adapting over time, and learning.
- Resilience builds across layers, from assets and routes to whole networks, the economy, and society.
- By mode, rail has the most mature assessment standards, roads have the most developed methods for calculating avoided losses, and aviation and maritime often need bespoke analysis. Across all modes, monetisation is partial, so important benefits are left unmeasured.
- Major gaps include: a unified way to value avoided losses, weak treatment of interdependencies, limited routes for non-monetised appraisal, and resilience standards that are emerging but not yet settled.

What changes are proposed

The report introduces a framework to bring a consistent and proportional approach for appraising resilience into TAG:

1. *Scope.* Appraise incidents that last more than six hours to avoid double counting with day-to-day reliability impacts and to focus analytical time on severe shocks.
2. *Clear boundaries.* Resilience concerns high-impact, non-routine shocks on known or expected journeys which is different from reliability (relates to routine variability) and from option value (relates to unknown journeys and latent demand).
3. *Three assessment dimensions.*
 - Strategic: Set a proportionate appraisal scope based on how central resilience is to objectives, and how material the impacts could be.
 - Economic: Use an expected value approach to quantify avoided losses.
 - Risk and uncertainty: Show the role of probabilities and provide switching values, plus incident evidence.
4. *Monetising avoided losses.* Transport models are built for normal conditions and do not typically capture long disruptions, so avoided losses need to be calculated bespoke. Capture:
 - User impacts such as extra journey time, vehicle costs, and associated welfare losses, and
 - Wider economic impacts where labour and capital are made idle by disruption.
 - If probabilities are robust, convert avoided losses to Net Present Social Value.
5. *Non monetised assessment.* Where evidence is thin, assess direction and likely scale using indicators such as peak to trough flow change, recovery time, number of users affected, and the availability of alternatives.
6. *Chronic risks.* Focus on acute events but include chronic risks where their link to acute risks is known. Where it is not known, consider chronic risks through separate resilience standards analysis.
7. *Other toolkits.* Keep CBA at the core, and use complementary methods, for example adaptive pathways or real options, where risks are particularly uncertain or dynamic.

How to report in TAG

- If monetised, report resilience as a Level 3 Indicative Impact.
- If non-monetised, report it in the Appraisal Summary Table.

- Create a new TAG Unit as a 'one stop shop' and undertake targeted updates to related Units.

Outstanding challenges

- Data gaps on network vulnerability, incident severity, duration, users affected, and risk probabilities.
- Modelling limitations, since standard transport models do not represent long-duration shocks well.
- Reconciling welfare and GVA results can be complex and resource intensive.
- Proportionality, because full monetisation is likely to be viable only for large schemes.
- System wide effects, which may need programme level appraisal rather than project by project analysis.

Priority research to unlock delivery

1. *Look up tables giving standardised expected disruption impacts by location, mode, and incident type, using data-led or model-led approaches, and covering user and wider economic impacts.*
2. *Exploring new advancements in modelling, including digital twins and system value models, to better capture interdependencies and cascading effects.*
3. *Behavioural evidence on how users value time and lateness under major disruptions, including differences by mode, and how these values rise with severity.*

Executive Summary

Purpose and context

In an increasingly volatile global landscape, the resilience of transport systems has become a strategic priority for safeguarding economic resilience and public safety. A combination of acute shocks (e.g., storms, cyber incidents, major accidents) and chronic stresses (e.g., climate change, ageing assets, demographic shifts, workforce shortages) is reshaping the risk landscape. The UK Government Resilience Framework (2022) and the 2025 Resilience Action Plan underscore the need for a more proactive, whole-system approach that better anticipates and manages disruption to the UK transport network.

Despite significant policy development, the Department for Transport (DfT) currently lacks a consistent approach for appraising resilience impacts within TAG. A literature review (Chapters 2–3) has been undertaken to establish the conceptual foundations for defining resilience, identifying relevant risks, examining existing appraisal practices, and understanding how resilience impacts can be distinguished from established TAG categories such as reliability or option value. Chapters 4 and 5 then set out a new Conceptual Framework and accompanying Recommendations for appraising resilience within TAG, promoting a systematic, proportional and coherent form of appraisal across transport modes and intervention types.

Key findings from the literature review

A literature review was undertaken using a Rapid Evidence Review methodology, drawing on over 200 sources of published literature and other non-published evidence, covering academic literature, government reports and grey literature in both the UK and globally. The key findings were:

1. Resilience should be defined through a multi-dimensional definition: *“The ability of the transport system to anticipate, withstand, recover from, adapt and learn from a wide range of shocks and stresses, to support connectivity, economic activity, environmental sustainability and social wellbeing”*.
2. Resilience builds across layers of the transport system: asset, asset-systems, routes, networks, economic and societal systems. Acute and chronic risks are becoming more frequent, severe, increasingly interconnected and often cascade across sectors (e.g., power, digital, water).
3. Rail has perhaps the most mature frameworks for resilience assessment (resilience standards, capability frameworks, early scenario based appraisal) whilst the most relevant methods for modelling avoided losses have been developed in a roads context. Maritime and aviation tend to require bespoke analysis. Across all modes, monetisation is partial or absent, and major resilience benefits remain unquantified.
4. Major appraisal gaps include: lack of a unified methodology for **monetising avoided losses**, **system interdependencies** are inconsistently captured, **non-monetised benefits** lack structured appraisal pathways and **standards for resilience** are emerging but not yet finalised.

The proposed conceptual framework for appraising resilience

A conceptual framework was developed to help address some of these gaps and provide consistent foundational principles. The main elements are:

- *Practical thresholds for resilience impacts*: resilience appraisal should include incidents that last over 6 hours to return to normal conditions. This removes double-counting with reliability appraisal.
- *Distinct from other TAG impact categories*: Resilience is distinct from reliability, which concerns day-to-day variability; resilience concerns high-impact, non-routine shocks. Resilience relates to known or expected journeys, whilst option value relates to unknown journeys and latent demand.
- *Assessment of three key dimensions*: strategic, economic and risk and uncertainty dimensions. The framework centres on economic assessment whilst recognising key linkages with other dimensions.
- *Strategic dimension*: plays a key role in establishing a clear and proportionate scope for economic appraisal. The primacy of resilience in the strategic objectives of the scheme, and the expected materiality of resilience impacts, should be the key factors guiding the level of analytical effort.
- *An expected value framework for quantifying avoided losses*: Major disruptions lead to significant impacts on users of the transport system and the economic activity the transport system helps to support. Avoiding these losses through additional resilience represents an increase in social welfare

in a welfare-based appraisal framework. Transport models are typically calibrated based on normal operating conditions and do not take account of long duration incidents that disrupt traffic flows. These impacts therefore need to be calculated separately in the economic appraisal. Resilience can reduce the expected value of losses through reducing the likelihood of a risk materialising and impacting the transport network, or reducing the loss if a risk does materialise. If risk probabilities can be robustly estimated, avoided loss impacts can be calculated in Net Present Social Value (NPSV) terms.

- *Avoided losses based on two impact categories:* (1) **Transport user impacts:** acute shocks result in significant delays to transport users, which are reflected in higher journey times, vehicle operating costs and other welfare losses. (2) **Wider economic impacts:** Unanticipated and short-run disruptions means that the current use of capital and labour is suddenly made idle and are not redeployed in alternative ways, resulting in a loss of economic value-added from businesses and their supply chains (reported separately from welfare-impacts).
- *Non-monetised economic assessment:* when sufficient evidence is not available, it may be more proportionate to appraise impacts through **non-monetised assessment**. In line with existing TAG Social and Environmental Impact guidance, this should assess both the directionality of the impact and the order of magnitude size of the impact. Reliable indicators upon which to base this assessment include peak-to-trough transport flow impacts, recovery period, number of users impacted and availability of alternative routes.
- *Additional emphasis on risk and uncertainty assessment;* If probabilities cannot be robustly estimated, probability switching values should be calculated. These should be communicated prominently, and supported by a clear risk narrative and evidence for incident frequencies on the transport network.
- *Appraisal of chronic risks:* the framework focusses on the appraisal of acute risks. If the relationship between chronic and acute risks are known, the assessment of acute risks can be amended to incorporate the impact of chronic risks. If the relationship is not known, chronic risks should be appraised separately through a resilience standards approach.
- *Acknowledging wider toolkits:* While CBA is the foundation of the conceptual framework, alternative approaches outside normal TAG applications could be considered (CEA, advanced decision frameworks, multi criteria frameworks, discount rate adjustments). Whilst these should not provide the main VfM frame of reference, these could help inform complementary appraisal methods. For example, when risks are complex, multi-dimensional or highly dynamic in nature, decision-making under uncertainty tools (such as adaptive pathways, real option analysis and portfolio analysis) could be applied.

TAG recommendations

Based on the conceptual framework, given its exploratory and innovative nature, resilience impacts should either be reported as a:

- Level 3 Indicative Impact if a monetised assessment has taken place, in line with DfT Value for Money framework; or
- Non-monetised impact in Appraisal Summary Table if a non-monetised assessment has taken place, in line with TAG Unit A4.1

A two-fold approach should be taken to update TAG to capture these impacts:

TAG Recommendation 1: Creating a new TAG Unit as a ‘one stop shop’ for consistent guidance relating to the appraisal of resilience;¹

TAG Recommendation 2: New research should be conducted to upgrade transport modelling tools, and develop new modelling approaches such as digital twins and systems resilience models.

Chapter 5 sets out a proposed TAG structure including strategic assessment (applicability, proportionality and resilience strategies), economic assessment (monetised avoided welfare losses, non-monetised avoided welfare losses and chronic risk appraisal) and risk and uncertainty assessment. Whilst no existing examples from the literature review fully demonstrate this guidance structure, case

¹ An alternative approach would be to integrate resilience impacts into TAG Units A1.3 and A2.1 however this may not fully pick up all relevant appraisal dimensions.

studies highlighting the economic assessment aspects of this framework have been identified: Lower Thames Crossing and Dawlish Exeter to Newton Abbot.

Developing a new TAG Unit in line with Section 5.2 is expected to have wider implications for other Units to ensure consistency across TAG (in particular, TAG Units A1.1, A1.3, M4, A2.1 and A4.1) – these units should be surgically updated to cite the interaction with resilience impacts

Outstanding analytical recommendations and priority research areas.

Implementing the conceptual framework in TAG faces several outstanding analytical challenges due to the uncertainty, dynamic, and systemic characteristics of the risks that resilience appraisal seeks to capture. Key challenges include:

- *Data gaps:* Risk thresholds would ideally be based on both incident delays and numbers of affected users that vary across transport modes – however existing data on impact severities is not readily available. Equally, reliable data on risk and incident probabilities is similarly often unavailable or uncertain.
- *Limitations of existing transport models:* Extrapolating welfare losses from transport models based on existing valuation parameters for day-to-day conditions are likely poor proxies for the welfare losses associated with unanticipated long-duration shocks.
- *Presentation of impacts:* DfT (2019b) demonstrated how welfare and GVA based forms of appraisal capture distinct impacts that can be robustly reconciled only through detailed analysis. Economic modelling approaches that are required to estimate ‘Indirect’ supply chain impacts and wider GDP impacts typically produce outputs in ‘GVA’ terms, that need to be reconciled with other ‘standardised’ impact estimations calculated in ‘Welfare’ terms. This could lead to substantive analytical effort.
- *Proportionality:* The complex data and analytical requirements to fully appraise resilience using monetised analysis may only be feasible for a limited number of major infrastructure schemes. A qualitative approach has been suggested as part of the conceptual framework however this provides limited information around the size of the potential impact. An alternative approach of providing quantitative look-up values for analysts to deploy efficiently in their appraisals is possible (see below).
- *Role for programmatic appraisal:* Project-level appraisal may fail to capture system-wide interdependencies and cascading benefits of resilience interventions. Programmatic appraisal may more accurately analyse these features but adds greater analytical complexity for analysts.

A series of recommendations for further empirical research have been made to overcome these appraisal challenges.

Recommended Further Research 1: New research is needed to develop look-up tables for resilience appraisal values. These tables could codify quantitatively the relationship between acute shocks of specific thresholds and expected losses in resilience impact categories. This would provide a monetised valuation of resilience for use in TAG appraisals. Such an exercise could undertake a data-led or model-led approach:

- A data-led approach would analyse disruption data, including cause, frequency, location, and duration at different spatial locations across transport networks, combined with data about normal traffic volumes and the presence of alternative routes at these locations. This could be used to build tables of expected disruption events and the expected scale of their direct transport user impacts and wider economic impacts.
- A model-led approach could replicate and analyse disruption scenarios by running transport and wider economic models to simulate both historic and theoretical future events where the expected duration of disruption events and the expected scale of impacts could be estimated.

This modelling could also distinguish threshold levels and expected values across modes – in particular, reflecting nuances in how transport modelling tools appraise journey time impacts across scheduled and unscheduled journey types.

Recommended Further Research 2: New modelling techniques such as total value systems and digital twin approaches should be further explored and a feasibility study undertaken. These approaches have

the benefit of capturing systemic value – for example the DfT Integrated Network Management Digital Twin (2024) codified many of these interdependencies in the transport system.

Recommended Further Research 3: Further research should look at how users respond to major acute shocks in valuing their time and examine the evolution of the perceived cost of travel time and lateness multipliers across higher delay scenarios for use in resilience appraisal. This work could use revealed or stated preference approaches and seek to identify any differences in values of time across modes.

1 Introduction

1.1 Background and Objectives

In an increasingly volatile global landscape, the resilience of transport systems has become a strategic priority for safeguarding economic security and public safety. The UK faces a range of interconnected challenges including climate change, cyber threats, geopolitical instability, and infrastructure degradation that all impact the resilience of its transport networks. The Covid-19 pandemic exposed significant vulnerabilities in the transport ecosystem to supply and demand-side risks, with some risks persisting and placing pressure on the long-term economic viability of certain modes of transport like bus networks.

The Government Resilience Framework (Cabinet Office, 2023a) committed to taking several actions for strengthening the UK resilience system. The 2025 UK Government Resilience Action Plan (Cabinet Office, 2025a) highlights the importance of strengthening the resilience of the UK's transport systems as part of its broader Critical National Infrastructure (CNI) agenda, recognising its central role in supporting the economy and responding to emergencies. By focusing on early action and collaboration across sectors, the government seeks to ensure that the economy can withstand and quickly recover from crises, helping to secure long-term economic stability and growth.

Resilience impacts are therefore becoming an increasingly important consideration in decision making around transport schemes. Although exploratory analysis of resilience impacts has been conducted in specific transport contexts, there is still no generally accepted approach for the economic appraisal of resilience impacts in DfT Transport Analysis Guidance (TAG).

The overall aim for this work is to recommend a robust, defensible basis for capturing resilience impacts within transport appraisal. This engagement has been delivered in three phases:

1. A systematic literature review of approaches to resilience appraisal
2. A conceptual economic framework for understanding and identifying resilience impacts
3. A series of recommendations for how resilience impacts could be represented within TAG with an outline of recommendations for future research to develop the framework further.

This document details the literature review of approaches to resilience appraisal within transport, and informs the conceptual economic framework and recommendations. It focuses on providing clear definitions for resilience in a transport context. It also explains the nature of risks and impacts facing the UK transport system and explores the existing practices for understanding and appraising such impacts – drawing on approaches utilised both inside government and externally in industry, academia and across global organisations. The appraisal of reliability within the contexts of highways and public transport is already well documented within TAG, and therefore this report will solely focus on resilience so that the two topics are clearly delineated.

1.2 Research Approach

The assessment has been conducted using a rapid evidence review methodology, adapted from the principles of the Rapid Evidence Assessment (Collins et al., 2015). This has included an extensive scan of the published literature and other non-published evidence.

This review was structured around three thematic areas, agreed in the Inception Meeting between DfT and PA Consulting:

- 1. Transport resilience policy, strategy and risks**
- 2. Existing transport resilience appraisal frameworks**
- 3. Methods for quantifying and valuing transport resilience impacts**

A systematic and thorough method was used to extract and synthesise evidence from an extensive survey of research including academic literature, government reports and grey literature with a focus on UK and international transport systems, while ensuring that the review was conducted proportionately and within the project's timeframe. Further details regarding the complete methodology can be found in Appendix A.

During the scoping stage of the project, a specific set of research questions was established in consultation with DfT project leads (see *Table 1*, below).

Table 1. Research questions underpinning the review. Source: PA Consulting analysis.

Section	Research Questions
<i>Transport resilience policy, strategy and risks</i>	<ul style="list-style-type: none"> • How is resilience best defined in the context of transport schemes? • How far are cross-government definitions appropriate? • What are the key strategic policy considerations for transport resilience that need to underpin the appraisal framework? • What are the most relevant and material acute and chronic risks that impact resilience in a transport context?
<i>Existing transport resilience appraisal frameworks</i>	<ul style="list-style-type: none"> • What forms of resilience have been appraised (e.g. route and network resilience), what are the common dimensions and how do they differ? • How is resilience currently being appraised across transport modes (including in resilience interventions and setting resilience standards)? • What costs and benefits have been evidenced from improvements in resilience in a transport context? • Which resilience impacts have been appraised quantitatively, and which qualitatively? • How far do these overlap with existing impacts (e.g. reliability and option value)? • Are there any relevant alternatives to cost-benefit-analysis (e.g. resilience standards/cost effectiveness analysis or wider uncertainty toolkits)? • How is resilience being considered in reaching value-for-money conclusions and factored into decision-making on transport investment?

The key findings from the literature review will be drawn together into a conceptual framework for appraising these impacts, defining the scope of appraisal, key appraisal principles and challenges, and developing the assessment approach across strategic, economic and risk and uncertainty dimensions. This will be based on the most mature/robust quantification and valuation approaches from the literature. It will also define any outstanding analytical challenges, data gaps or future research priorities.

A multi-disciplinary perspective has been adopted for this literature review, evaluating resilience across a wide array of appraisal formats (such as business cases, impact assessments, and policy appraisals), and considering these issues through multiple analytical perspectives (including both strategic and economic assessments). Lessons from other countries, sectors and other appraisal frameworks from HM Treasury Green Book supplementary guidance are drawn on throughout the review, where relevant.

The review's key findings are described in the main text with a range of case studies identified. These case studies are displayed in the following way:

CASE STUDY KEY TOPIC AREA

Finally, key findings that will inform the design of the conceptual framework are highlighted using call-out boxes, displayed as follows:

Key implication for the appraisal framework

Implication

1.3 Report Structure

This review is subdivided into the following chapters:

- **Chapter 2** explores definitions of resilience in a transport context used across the literature and within government, articulates strategic policy considerations that should underpin the appraisal framework and identifies the most relevant and material risks that need to be captured
- **Chapter 3** examines how resilience is currently appraised across transport modes, identifies the key costs and benefits of resilience improvements in a transport context, and examines different Value for Money frameworks in appraising resilience and informing decision-making
- **Chapter 4** sets out an initial conceptual framework for appraising resilience in a transport context. It draws together the key insights from the literature review to: define the scope of resilience appraisal, explain the relationship between resilience impacts and existing TAG categories, introduces key principles and appraisal challenges and proposes approaches for strategic, economic (both monetised and non-monetised) and risk and uncertainty assessment.
- **Chapter 5** identifies key recommendations for how the appraisal of resilience should be incorporated into TAG. It highlights the key implications of the conceptual framework, sets out a proposed TAG structure and summarises the key aspects of guidance that should be contained within this. The next steps for developing TAG guidance are identified, and required new areas of research highlighted. Interactions with other aspects of TAG are considered, and three case studies representing example applications of this guidance are presented.

Chapters 4 and 5 have been developed to be read together on a standalone basis – relevant material from Chapters 2 and 3 has therefore been summarised and included where this context is required.

Appendix A explains the Rapid Evidence Review methodology undertaken and **Appendix B and C** provides summary tables of key evidence and case studies. **Appendix D** provides the Rapid Evidence Review findings, assessing the relevance and importance of each source in driving the key findings. A full list of sources and references is also provided.

2 Transport Resilience, Policy, Strategy, and Risks

2.1 Defining Resilience in a Transport Context

This section considers how resilience is best defined in the context of transport schemes and explores the extent to which cross-government definitions are appropriate. It considers how resilience can be best understood at different ‘layers’ of the transport system (see Figure 1), and the types of risks and outcomes relevant to the transport sector and for which the DfT is lead government department. This section concludes by distinguishing the concepts of resilience, reliability and robustness in a transport context. In this section we address the following research question:

Key research question: *How is resilience best defined in the context of transport schemes and how far are cross-government definitions appropriate?*

2.1.1 Defining Resilience

Whilst the concept of resilience is frequently used across different disciplines, there is no single agreed definition. Definitions have evolved in different ways, encompassing ideas such as absorbing shocks and persisting (systems thinking), recovering from hazards (disaster management), self-organisation and adaptation (social-ecological systems), maintaining effectiveness despite stressors (defence systems), and the capacity for rapid recovery and learning (community and national resilience). Over time, resilience has shifted from simply resisting and bouncing back from disruptions to including adaptation, thriving in changing environments, and transformation for long-term improvement. Money et al. (2017) characterises resilience as “*The ability of systems (including infrastructure, government, business and communities) to proactively resist, absorb, recover from, or adapt to, disruption within a timeframe which is tolerable from a social, economic, cultural and environmental perspective*”.

Modern frameworks, such as the UK Government Resilience Framework (2023), emphasise ‘whole of society’ resilience, requiring collaboration across sectors to develop a shared understanding of and response to risks. These risks are typically delineated into sudden, acute shocks and ongoing, chronic stresses. Most recently, the 2025 UK Government Resilience Action Plan (Cabinet Office, 2025a) defines resilience as:



Resilience: “*The ability to anticipate, assess, prevent, mitigate, validate, respond to, and recover and learn from natural hazards, deliberate attacks, geopolitical instability, disease outbreaks, and other disruptive events, civil emergencies or threats to our way of life.*” (Cabinet Office, 2025a)

This aligns with the International Organization for Standardization (ISO) definition of resilience, which is the “*ability to absorb and adapt in a changing environment*” (ISO, 2021).

2.1.2 The Evolving Study of Resilience in a Transport Context

In line with the broader literature, the concept of resilience in a transport setting has evolved to capture a broad set of attributes over time. The academic discussion has advanced from focussing on the transport system’s ability to withstand and absorb shocks, to its capacity for rapid recovery and continued functionality, and recently towards more nuanced characteristics such as redundancy, adaptability, and resourcefulness. Some studies have defined resilience from the perspective of the overall transport system, whereas others have focused on specific modes. Table 2 below demonstrates how such definitions have evolved:

Table 2. *Evolving definitions of resilience in the context of transport schemes.*

Source	Mode	Definition
Murray-Tuite (2006)	Road	Characteristic indicating (1) system performance under abnormal conditions, and (2) the speed and resources required for recovery to original functional states. Ten dimensions: redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly.

Ta et al. (2009)	Multi-modal	"The ability for the system to absorb the consequences of disruptions to reduce the impacts of disruptions and maintain freight mobility."
Mansouri et al. (2009)	Maritime	"A function of system's vulnerability against potential disruption, and its adaptive capacity in recovering to an acceptable level of service within a reasonable timeframe after being affected."
Nair et al. (2010)	Multi-modal	"The post-disaster expected fraction of demand that, for a given network configuration, can be satisfied within specified recovery costs (budgetary, temporal, and physical)."
Serulle et al. (2011)	Multi-modal	The ability of the transportation system to (1) absorb disruptive events gracefully and (2) restore its pre-disruption level of service in a specified time frame
Beiler et al. (2013)	Road	Emphasises four properties: robustness, redundancy, resourcefulness, and rapidity.
Bhavathrathan and Patil (2015)	Road	"A measure of maximum agitation a system can take in before getting displaced from one state to another."
Janić (2015)	Aviation	"The ability to withstand and stay operational at the required level of safety during the impact of a given disruptive event."
Chan and Schofer (2016)	Rail	"The ability to experience a negative, potentially damaging event and return to a healthy state of operations in a reasonable amount of time after that event."
Money et al. (2017)	Multi-modal	"Resilience is the ability of systems (including infrastructure, government, business and communities) to proactively resist, absorb, recover from, or adapt to, disruption within a timeframe which is tolerable from a social, economic, cultural and environmental perspective."
Ganin et al. (2017)	Road	"System recovery from additional disruptions"
Kurth, Kozlowski et al. (2020)	Multi-modal	"Resilience in transportation manifests is the ability to function in spite of disruption and/or recover function rapidly following disruption."
Kazmia et al (2023)	Road	Resilient infrastructures are not only secure, but they are also able to bounce back when disruption hits the network. They endure the adverse effects and return the network quickly to its normal conditions.

Strategic transport and wider infrastructure policy is increasingly recognising the importance of resilience, driven by a growing awareness of the need for long-term, system-wide thinking. Policy development in this space has also offered some definitions of resilience in a transport context:

- **The Second National Infrastructure Assessment, National Infrastructure Commission (2023):** *"Resilience will involve ensuring that existing systems can withstand shocks. It will also mean managing uncertainty to adapt to changing threats."*
- **Developing Resilience Standards in UK Infrastructure Resilience, National Infrastructure Commission (2024):** *"Resilience in infrastructure refers to the ability of systems to anticipate, withstand, recover from, and adapt to a wide range of shocks and stresses, ranging from climate change and cyber threats to operational failures and aging assets. The interdependencies between transport and other infrastructure systems (e.g. energy, digital) are highlighted"*
- **Transport system resilience, UK Parliament (2025):** *"Transport system resilience refers to the sector's capacity to deal with, adapt to and recover from disruptions."*

On a global scale, the International Transport Forum (2025) define the resilience of transport networks as *"the capability of transport networks to prevent, respond and adapt to disruptions"*. All these examples

are consistent in defining resilience in the context of the ability of transport systems to anticipate, absorb, recover from, and adapt to a range of shocks and stresses.

2.1.3 Recommending a Definition of Resilience for TAG

The appropriate definition of resilience for TAG guidance should be in line with accepted UK definitions of resilience, and in line with the broader literature, whilst remaining practical and meaningful within the specific context of transport appraisal.

The broad Cabinet Office definition of resilience for national-level policymaking should be translated into operational terms for transport appraisal that reflect the unique characteristics of the transport system's physical infrastructure, network interdependencies, and economic connectivity.

Table 3 seeks to undertake this translation, using Field's (2025) framework for decomposing resilience from a definitional perspective:

Table 3. Distinguishing resilience in a national policy context and a transport appraisal context. Source: PA analysis

	Cabinet Office definition	Transport appraisal interpretation
Type of system impacted (Resilience "of what")	The overall UK societal system	The transport system (including infrastructure, services, operators, networks) and sectors of the economy that are dependent on it
Type of risk and/or threat (Resilience "to what")	Acute shocks and chronic stresses. Including disruptive events, civil emergencies or threats to society's way of life	Acute shocks and chronic stresses, whether external or internal to the transport system
Type of outcome (Resilience "for what")	Long-term stability across economic, social and environmental systems	Continued provision, protection and connection for transport users during disruptions, enabling secure access to goods and services, and supporting economic activity and social wellbeing
Type of economic agent (Resilience "for whom")	All of society	All of society, with specific emphasis on transport users (passengers, freight customers), staff, operators, and dependent sectors

In summary; the relevant definition in a transport appraisal context might be: ***"The ability of the transport system to anticipate, withstand, recover from, adapt and learn from a wide range of shocks and stresses to support connectivity, economic activity, environmental sustainability and social wellbeing"***.

Selecting the Appropriate System

Careful consideration needs to be given to defining the boundaries of the 'system' in the definition of resilience for transport appraisal. A systems approach encourages understanding of the broad purpose and scope of a system, rather than a component-centric siloed view (Field and Look, 2018). On this basis, there is increasing recognition of the role that the transport system plays within the overall economic system, which emphasises the continuity and performance of transport networks as enablers of economic activity.

Figure 1 presents a layered model of the 'hard infrastructure' systems involved in delivering resilience in a transport context. This spans from the resilience of the most granular physical components of transport infrastructure to broader societal impacts outside the transport system. This layered approach highlights how resilience is built cumulatively across each level, where resilient outcomes within each level reinforces the next. Weaknesses at lower levels (e.g. asset failure) can cascade upward, while strong design and planning at higher levels (e.g. economic policy) can buffer and support the system as a whole.

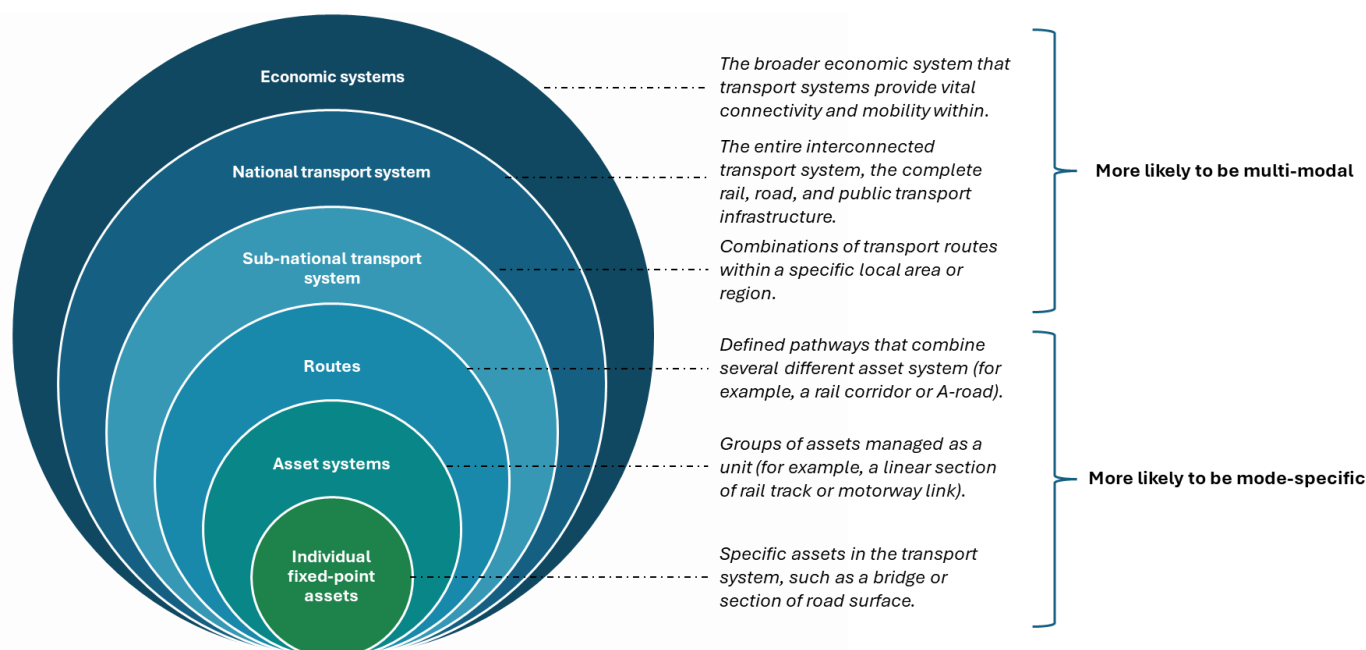
At the core of transport systems are **individual fixed-point assets**, such as bridges, stations, and tunnels which must be physically robust, reliable and resilient. As Kazima et al. (2023) highlight, resilient infrastructure is both secure and capable of recovering from network disruption. These assets are

organised into **asset systems** (e.g. a linear rail or motorway section), requiring coordination across fixed, linear, and mobile components. These systems connect to form **routes**, such as a rail corridor or A-roads. **Sub-national transport networks** integrate these routes and enable movement across modes and local areas to deliver regional accessibility, while **national networks** ensure cohesion and connectivity across the country.

The structure and characteristics of these networks are critical to supporting economic activity undertaken by the transport users they serve. For instance, the availability of alternative routes or the concentration of high-value business activity can significantly influence the consequences of failure (Bergantino et al., 2024). At the outermost layer, **economic systems** depend on the resilience of all inner layers to maintain supply chains, labour mobility, and overall economic stability. As noted in the *Transport Network Resilience* policy paper by the International Transport Forum (2025), transport networks are particularly vulnerable due to their interdependencies both within transport systems and with external sectors, particularly power networks.

Individual assets, asset systems and routes likely represent mode-specific infrastructure whilst wider transport and economic systems typically capture numerous modalities. It should also be noted that people are critical components of the whole system whether they are users of the systems or staff with the necessary skills base. Likewise, the economic system sits alongside broader societal systems where transport systems can support connectivity and mobility to enable **community, environmental and societal resilience**, especially when transport infrastructure promotes nature-based solutions and transport-oriented developments.

Figure 1: The layers of transportation systems. Source: PA Consulting analysis.



Evidence from the UK's National Infrastructure Commission (2020) reinforces this layered view of transport resilience, with case studies showing how asset failures, such as the 2015 Forth Road Bridge closure, can cascade through the system disrupting regional economies and emphasising the need for resilience at every layer.

This framework also provides the foundation for understanding resilience appraisals undertaken in mode-specific contexts. For example, the Resilience Technical Annex in the Appraisal Manual by National Highways (2022a) delineates between 'route' and 'network' resilience, in a road context (see below, which is explored further in Section 3.2.2). Clearly defining these distinctions is crucial for determining the scope of impacts and selecting appropriate metrics for assessment, ensuring that the appraisal is well-targeted:



Route resilience: “the ability of the road improvement itself to cope with major planned or unplanned incidents or closures”

Network resilience: “the extra capability that the road improvement gives to the wider network to cope with major planned and unplanned incidents or closures elsewhere.”

Types of Risks and Threats

Transport systems are exposed to a wide range of risks and threats, all of which can significantly disrupt operations, safety, and broader societal functions. These include **acute shocks** (Section 2.3.5), such as extreme weather events or cyberattacks, as well as **chronic stresses** (Section 2.3.6) like rising temperatures and sea levels or ageing assets. ISO (2024) defines a shock as an “*uncertain, abrupt or long-onset event that has potential to impact upon the purpose or objectives of an urban system,*” and a stress as “*chronic and ongoing dynamic pressure with the potential for cumulative impacts on the ability and capacity of the system to achieve its objectives.*”

Janic (2018) further classifies acute shocks as either **external shocks** (such as natural disasters, cyberattacks, or economic crises), or **internal disruptions** that originate within the transport system itself (including equipment failures or operational errors). Internal disruptions can be either be **unplanned** (i.e. from an acute shock such as an extreme weather event) or **planned** (i.e. due to maintenance closures either of the route itself or of structures that the route crosses or that cross the route).

The Third UK Climate Committee Risk Assessment (2022) identified eight priority climate risk areas requiring urgent attention from 2021-2023, spanning both acute and chronic dimensions.

The CCRA3 report (Betts and Brown, 2021) described how the transport system is highly interconnected with other vital systems in the economy (such as the energy system) and disruptions in one system – whether due to flooding, heat stress, or infrastructure failure – can quickly cascade to other systems, amplifying the impact of hazards and impeding recovery efforts.

Section 2.3 provides a more detailed examination of the most relevant risks and threats in the context of the transport system.

Types of Outcomes

The World Bank (2025) defines the transport system as “fundamental to supporting economic growth, creating jobs and connecting people to essential services such as healthcare or education”. Transport networks support growth and jobs through connecting individuals to employment opportunities and workplaces and facilitating the movement of goods and services.

The economic benefits from the smooth functioning of the transport system differ between the mode of transport and the scale of the infrastructure being analysed, and the local demand and economic context observed (Frontier Economics, 2024). The linkages between the transport system and the economy are captured in DfT TAG’s ‘Wider Economic Impacts Appraisal’ (2025a) citing how transport investment can deliver wider economic impacts through inducing **additional investment** (Venables et al., 2014), **facilitating employment opportunities** (Bastiaanssen, et al., 2022) and **boosting productivity** (Pogonyi et al., 2021).

Similarly, transport disruptions may also disrupt sectoral supply chains and prevent workers accessing their places of work, which can lead to reduced investment, employment and productivity. The Second National Infrastructure Assessment (National Infrastructure Commission, 2023) highlights that “*where more resilient infrastructure can anticipate and resist or absorb shocks, it can prevent economic damage by improving the reliability and predictability of services. Where it cannot, a focus on fast recovery can improve quality of life and reduce disruption costs.*” In the long-term poor transport resilience makes a local area or region less conducive to growth, less attractive for firms to invest in and for workers to work in (Ahmad and Al-Bazi, 2023).

National Highway’s 2017 Strategic Economic Growth Plan finds that whilst businesses in general require the Strategic Road Network (SRN) to provide good connectivity, some sectors of the economy are particularly reliant. For example, this includes businesses serving multiple regions across the UK (i.e. large retailers) or businesses using international gateways to facilitate access to markets (i.e. logistics companies). Better connectivity is seen to influence the location of industrial hubs and future land use.

To conceptualise resilience outcomes more clearly, they can be grouped into three broad categories:

- **Service Outcomes:** Resilience provides the ability to maintain core functionality in the wake of acute shocks and to restore operations swiftly and effectively. These outcomes are often measured through indicators such as network availability, recovery time, and operational continuity.

- **User and Economic Outcomes:** Resilience may mitigate disruption-related costs, such as delays for individuals and businesses, and lost value added. Over time, resilience may contribute to broader economic outcomes such as regional competitiveness, productivity growth and economic development.
- **Social Outcomes:** Resilience safeguards access to essential services including healthcare, education, and employment, in the wake of acute shocks.

These outcomes are linked through causal pathways. For example: a flood event (shock) may close a major road (transport disruption), reducing accessibility for workers and freight (service impact), which in turn leads to lost output and missed deliveries (economic impact), and reduced access to healthcare or education (social impact). Patterns of repeated disruption could conceivably have longer-term effects such as deterring firm investment and/or location decisions.

The appraisal of resilience should seek to capture each of these outcomes, if it is feasible to do so.

2.1.4 Distinguishing Concepts Related to Resilience

Robustness, reliability, recovery and redundancy are terms often used interchangeably when discussing resilience and whilst these concepts are complementary, each represent distinct characteristics of the transport system. It should be noted that the concepts of robustness, recovery, and redundancy are key components of resilience, which is distinct from reliability as discussed below.

Reliability



Reliability: “Reliability refers to variation in journey times that individuals are unable to predict, such as day-to-day variability from recurring congestion or non-recurring incidents. Predictable variation, such as time-of-day or seasonal effects, is excluded.” (Department for Transport, 2025b)

Reliability refers to the consistent and predictable performance of a system under normal operating conditions, such as punctual services and dependable infrastructure. In contrast, resilience is concerned with how a system behaves under the instance of significant stress or disruptive events outside of business as usual.

In practical terms, a transport system can be highly reliable yet fragile, where day-to-day performance is satisfactory, but which lacks the capacity to absorb or recover from unexpected events (Mattsson and Jenelius, 2015). A resilient system, on the other hand, may experience occasional variability but is designed to withstand major disruptions, ensuring continuity of service. A heavily interconnected multi-modal urban transit system with significant constraints on ongoing maintenance expenditure might be one example of this – with significant capacity and redundancy to offer alternative routes during shocks but vulnerable to regular smaller-scale failures and user and delay variance.

Robustness



Robustness: “Robustness is the ability of a system to resist against adverse actions or events ... In different words, a system is called robust if it may cope with changes without the need to adapt.” (Ge, L., Voß, S., and Xie, L., 2022)

The International Transport Forum (2025) describes robustness of the transport system as an important contributor to resilience, determining the extent to which a deterioration of a system’s functions is due to the disruption. The more robust a system, the less the system functions are affected. Strategies to increase robustness strengthen the transport system and reduce its vulnerability to shocks and stresses.

While a robust transport system can withstand shocks and maintain its core functions during unexpected events, it may still face challenges if disruptions exceed the system’s design thresholds. Resilient systems go further, combining robustness with adaptive strategies to ensure continuity and rapid response even when facing events beyond ‘routine’ resistance. In this way, resilience enhances robustness by preparing the system not just to absorb disturbances, but also to adjust and maintain service under a wider range of conditions.

Recovery



Recovery: “Recovery is ... the process of rebuilding, restoring and rehabilitating the community following an emergency.” (Cabinet Office, 2013)

Recovery is the period required for a transport system to return to its pre-disruption level of service or operation. It encompasses the actions and time needed to restore normal functioning after an incident. Recovery may take months or years to complete, involving both the reconstruction of the physical infrastructure and restoration of emotional, social and physical well-being. This process continues until the disruption has been rectified, demands on services have been returned to normal levels, and the needs of those affected have been met. ISO (2021) definition of recovery closely aligns with this, the “*restoration and improvement, of operations, facilities, livelihoods or living conditions of affected organizations, including efforts to reduce risk factors.*”

Although a system with strong recovery capabilities can restore operations after disruption, recovery alone does not guarantee that the losses felt by users because of the incident are minimised. Truly resilient transport networks integrate swift recovery into a broader capacity to limit service loss and support affected communities throughout and after a disruption. Resilience is thus not only about returning to normal, but also about minimising the duration and severity of adverse effects, providing both immediate and long-term relief. Importantly, resilience also encompasses transformative learning, enabling systems to adapt and improve based on lessons learned from disruptions.

Redundancy



Redundancy: “Redundancy refers to the presence of alternative ways to execute a system's intended function through adaptation of the system's elements or units that previously served other purposes.” (Gerges et al., 2022)

Redundancy describes the built-in capability of a network or asset to maintain operations by providing alternative resources, routes, or spare capacity when part of the system is compromised. It ensures that backup options are available so essential services can continue during disruptions.

Redundant systems limit vulnerability by offering alternative routes or resources when part of the network fails, helping to sustain operations during disturbances. However, redundancy without an overarching resilience strategy may leave the system exposed if backup options are underprepared, poorly maintained, or unable to adapt to complex or prolonged failures. Resilient systems leverage redundancy as one aspect of their design, ensuring backup capacities are integrated and flexible enough to meet a wide array of challenges. Redundancy is highly linked to the concept of option value – explained further in Section 3.3.4.

2.1.5 The Adaptive Capacity of Transport Systems

Understanding Adaptive Capacity

ISO (2021) defines adaptive capacity as the “*combination of all strengths, attributes, and resources available within a community, organization, or society to manage and reduce disaster risks and strengthen resilience.*”

Adaptive capacity refers specifically to the capability of systems, such as people, processes, assets, and technologies, to reorganise effectively in response to evolving risks and disruptive events. Adaptive capacity is typically agnostic of risk type and enhances overall system performance through all phases of disruption and recovery. It relates to a system being able to adjust to any potential change and effectively respond and recover from shocks quickly, reducing the overall impact of the shock as well as the ability to capitalise on opportunities when they present themselves (Field et al., 2017). Some of the economic literature distinguishes between absorptive, adaptive, and restorative capacities (Biringer et al., 2013; Vugrin et al., 2011):

- **Absorptive capacity** – the ability of the economy to minimise the initial impact of any disruption.
- **Adaptive capacity** – the ability of the economy to reorganise itself in response to disruption to minimise its impact.
- **Restorative capacity** – the ability of the economy to recover back to the economy's initial standing.

The literature finds that adaptive capacity has the highest impact on system performance from the onset of a disruptive event until recovery. However, it can also enable the transport system to adapt and thrive in normal times, through an improved ability for users of the system to work together to anticipate opportunities and capitalise on them, and to collaborate and problem solve (Field et al, 2024).

Other authors note the dynamic nature of adaptive capacity, including the importance of learning from prior shocks. For example, Rose and Liao (2005) analysed this in the context of natural disasters and coined the concept of “adaptive resilience”. This reflects the ability to innovate or put in extra effort during crises. Adaptive capacity is key to the UK Government Resilience Framework, which emphasises the importance of adapting to evolving risks for long-term resilience.

Adaptive Capacity in a Transport Context

In line with this wider literature in the context of transport appraisal, resilience must be understood as more than just physical durability, it encompasses:

- System design (e.g. redundancy, flexibility),
- Operational strategies (e.g. contingency planning),
- Policy frameworks (e.g. investment in adaptive infrastructure)

In transport, adaptive capacity may also be realised through measures such as scenario planning, investment in workforce skills and new technologies, clear roles and responsibilities, and building contingency into supply chains (see [Case Study 1](#)). These strategies may allow transport organisations to better anticipate and plan for both acute and chronic risks, minimising disruption and shortening recovery times.

Case Study 1

Enhancing adaptive capacity in Rail Delivery Group

The Rail Delivery Group (RDG) has taken a proactive, structured approach to advancing organisational resilience and adaptive capacity across the rail sector. Through implementation of the Integrated Emergency Management (IEM) framework, RDG has broadened its focus from physical assets to include the development of effective leadership, staff competencies, and a culture of continuous learning. The framework establishes clear accountability for senior leaders, who are responsible for driving resilience strategy and maintaining sustained investment.

Key features of RDG’s approach include comprehensive workforce training, real-time risk monitoring, and the adoption of recognised maturity models, such as the Office of Rail and Road’s Risk Management Maturity Model (RM3), to measure progress and guide improvement. RDG has also recently published a resilience competency framework and organisational maturity model, developed with PA Consulting (Rail Delivery Group and PA Consulting, 2025a), to assess and build individual and organisational capabilities.

Inclusive engagement is emphasised, with resilience embedded into daily operations through ongoing review of Key Performance Indicators (KPIs) and Key Risk Indicators (KRIs). Prioritising flexibility, collaborative learning, and cross-functional teamwork, RDG’s resilience strategy ensures the sector is well-prepared to anticipate, manage, and recover from both immediate disruptions and long-term challenges. This approach sets a benchmark for adaptive capacity within UK transport.

Image 1. TransPennine Express Train at Newcastle Central Station. The RDG would be involved in setting the overall policy and communication standards that TransPennine Express, as a member of the rail industry, must adhere to.



This photo by [David Dixon](#) is licensed under [CC BY-SA 2.0](#).

Key Findings

- Resilience is a **multidimensional and evolving** concept, reflecting the transport system's ability to withstand, adapt to, and recover from both acute shocks and chronic stresses, requiring a collaborative, system-wide approach.
- While multiple definitions exist, modern frameworks emphasise the role of **adaptation**. Resilience in a transport context now means not only bouncing back after disruption, but also learning, transforming, and thriving under changing conditions.
- The resilience of the transport system **builds cumulatively** across several layers, from individual fixed-point assets through networks and economic systems, with weaknesses at lower levels cascading upward and strong policy and planning at higher levels providing system-wide support.
- **Risks and threats to transport systems are diverse**, ranging from external acute shocks, internal disruptions, and chronic stresses, often with cascading impacts on other economic sectors.
- Resilience in transport explicitly **supports social mobility and connectivity**, underpinning productivity, access to essential services, and wider economic impacts. Disruptions can lead to reduced investment, employment, and productivity, especially in sectors highly dependent on transport, as well as distributional impacts, access to opportunities, and overall community well-being.
- The following concepts are all distinct but related to resilience: **Reliability** – consistent performance under normal conditions; **Robustness** – ability to resist degradation during disruption; **Recovery** – speed of returning to normal after disruption; **Redundancy** – availability of alternatives.
- Adaptive capacity is the ability of transport systems to adjust and improve in response to changing risks and threats. It is increasingly central, underlining that **resilience is not just about durability, but about system design, flexible operations, and investment in adaptation**.
- A suitable definition for resilience in transport appraisal might be: *The ability of the transport system to anticipate, withstand, recover from, adapt and learn from a wide range of shocks and stresses to support connectivity, economic activity, environmental sustainability and social wellbeing*

2.2 Strategic Policy Considerations

This section explores UK Government policy-making relevant to resilience in a transport context. It considers the role of the UK Government Resilience Framework, UK Resilience Action Plan, DfT strategic policymaking, and wider UK policy developments for improving the resilience of transport systems. This section also examines how this policy framework should guide and underpin the appraisal of resilience in a transport context. In this section we address the following research question:

Key research question: *What are the key strategic policy considerations for transport resilience that need to underpin the appraisal framework?*

2.2.1 UK Strategic Policy Making Relevant to Resilience in Transport

UK Government Resilience Framework

In December 2022, the UK Government Resilience Framework was established. This sought to **coordinate UK strategic policy making** across departments by strengthening the foundational systems and capabilities underpinning national resilience, promoting a whole-of-government and whole-of-society approach to anticipating and responding to all civil contingencies risks. The Framework sets out three key strategic policy principles:

- Develop and share a comprehensive understanding of the civil contingencies risks faced by the UK.
- Focus on prevention and preparation wherever possible prioritising proactive measures rather than relying solely on response ('prevention rather than cure').
- Adopt a 'whole of society' approach to resilience, increasing transparency and empowering everyone (across government, business, voluntary sector, and communities) to contribute.

Recent efforts have focused on **strengthening system-wide resilience**, particularly within CNI and critical supply chains. The Framework introduced new policy approaches in areas like cyber resilience and crisis management, aiming to embed resilience into proactive policymaking and investment, rather than relying solely on crisis response.

The Framework **explicitly identifies transport infrastructure** as a form of Critical National Infrastructure (CNI). It states: *"the government has a well-established approach for identifying, assessing and managing risks to the UK's people, economy and critical national infrastructure (CNI), such as ... transport, energy, communications, food and water supplies"*. The resilience of the transport system, which includes roads, railways, ports, and airports is recognised as fundamental to the UK's overall national resilience. It emphasises coordinated efforts and investment in infrastructure as essential for **protecting transport networks** and ensuring the continuity of vital services during emergencies. Maintaining transport system functionality during shocks is essential, as these networks play a critical role in emergency response and supporting wider societal needs.

UK Resilience Action Plan

The Resilience Action Plan was launched in July 2025 and is designed to put the policy principles of the UK Government Resilience Framework into practice. It identified **specific objectives, timelines, and accountability mechanisms** to strengthen the UK's resilience system across sectors, to deliver against three key objectives:

1. Continuously assess how resilient the UK is to target interventions and resources effectively
2. Enable the 'whole of society' to take action to increase resilience
3. Strengthen the core public sector resilience system

The Action Plan also recognises transport infrastructure as part of the UK's CNI whose disruption would severely impact national security, public safety, or economic stability. It sets out coordinated measures to **improve the resilience of transport systems** to risks like extreme weather, cyber threats, and supply chain disruptions. This is through actions such as:

- Enhancing risk assessment and data-sharing for transport networks
- Requiring infrastructure operators to integrate adaptation and preparedness into planning
- Supporting investment in resilient infrastructure and technologies
- Testing and exercising emergency response plans involving transport partners

These measures aim to help the transport sector be better prepared not just for immediate incidents, but also for long-term chronic risks, aligning with the broader national resilience objectives set out in the original Framework. The Framework and Action Plan did not announce new centralised funding for resilience, and funding will instead be established by departments as part of balanced programmes of investment that seek to achieve a broad range of departmental objectives.

DfT and Wider Transport Bodies' Resilience Strategies and Policies

As part of the **Cabinet Office CNI resilience framework**, the transport sector is expected to develop and maintain a **Sector Security and Resilience Plan (SSRP)**. These plans outline how the sector will:

- Identify and protect critical assets
- Mitigate risks from all hazards, including severe weather, storms, pandemics, cyber and operational threats
- Ensure continuity of essential services during emergencies
- Coordinate with government and industry stakeholders.

While the full SSRP for transport is not publicly available, the DfT works closely with National Highways, Network Rail, and other operators to implement resilience strategies aligned with this framework. These include infrastructure hardening, emergency response protocols, and cyber security measures.

In 2025, **DfT and the Met Office released the Transport Hazard Summary Series** which included the paper *Transport hazard summary: Hazards, risks and resilience, Department for Transport (2025d)*. This information sheet provides an overview of the principles of risk identification, assessment and mitigation or adaptation that should be put in place by industry bodies when designing measures to build resilience across road, rail, aviation and maritime sectors. It highlights the importance of addressing all phases of the resilience cycle by regularly assessing risks, developing plans and test scenarios and implementing lessons learned to enhance resilience at each stage. Further summaries in the series focus on specific hazards and provides examples of strategies that have been, or could be deployed to mitigate vulnerability and support recovery.

Figure 2. DfT and Met Office Resilience Cycle. Source: Transport Hazards Summary: Risks and Resilience, Department for Transport (2025c)

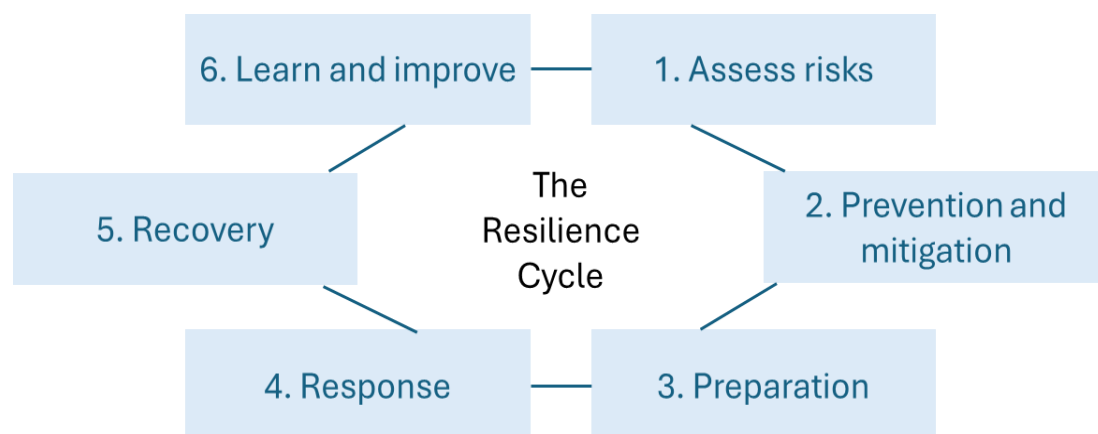


Figure 2 presents a simplified version of the resilience cycle, intended as a foundational overview. While intentionally high-level, this framework offers an entry point into how risk can be assessed and managed. A more detailed representation is provided in Figure 3, and DfT are undertaking work to set out what the Resilience Action Plan means in practise for the transport sector for the next five to ten years.

DfT's Climate Adaptation Strategy for Transport (CAST) emphasised the strong support for a more strategic, cross-sectoral approach to resilience planning. A supporting [consultation](#) highlighted embedding climate adaptation into strategic transport policymaking as a core, routine activity rather than a reactive measure. Respondents including transport operators, local authorities, and industry bodies emphasised the need for cross-sector collaboration, recognising that many resilience challenges and solutions lie outside the transport sector. There was a clear call for better integration of climate risk into investment decisions, supported by improved data, tools, and long-term funding. Importantly, stakeholders highlighted the complexity of appraising adaptation interventions, noting that traditional transport appraisal methods may not fully capture systemic risks or cascading impacts, and that interdepartmental coordination and broader expertise are essential for effective resilience planning.

The consultation conclusions build on **DfT's 'Fit for a changing climate?' report (2024a)** which outlines a shift toward a system-wide, proactive approach to climate adaptation in transport, recognising that resilience must be embedded across planning, investment, regulation, and operations. The strategy proposes integrating climate risk into economic appraisal, regulatory frameworks, and funding decisions, supported by improved data, modelling, and guidance. It also highlights the importance of mainstreaming adaptation into business-as-usual processes, rather than treating it as a separate or reactive issue. This approach aims to protect transport systems from climate impacts, whilst contributing to wider societal resilience. The resulting strategy (CAST) published in 2025, provides a vision for 'a well-adapted transport system that is resilient to the changing climate'.

Transport delivery bodies such as Network Rail (NR) and National Highways (NH) are increasingly highlighting resilience as a key priority, highlighting the importance of managing asset condition, integration across modes of transport and strengthening design standards. The following table summarises the most recent resilience strategies across key transport modes and highlights the strategic policy considerations relevant to each:

Table 4. Recent transport resilience strategies and policy consideration. Source: PA Consulting analysis of multiple sources (listed)

Transport Body	Most Recent Resilience Strategy/ Policy	Strategic Policy Considerations Relevant to the Transport Sector
Aviation	<i>Airspace Modernisation Strategy 2023-2040, CAA (2023)</i>	Emphasises buffer capacity, collaboration between airlines, airports, and regulators, improved use of data, anticipation of cyber/physical threats, emergency response planning, and learning from past disruptions to adapt future operations.
Bus / Public Transport	<i>Climate Change Adaptation Plan, TfL (2023)</i>	Building on TfL's 2010/11 Resilience Management Framework, the 2023 Adaptation Plan focuses on adapting London's transport system to increasing climate risks such as heatwaves, flooding, and storms. Integrates climate risk into governance and planning through forecasting and adverse weather protocols, investing in green infrastructure (e.g. rain gardens, street trees), and improving customer communication during disruptions. The plan supports reliable public transport services, aligned with the Mayor's Transport Strategy and TfL's Corporate Environment Plan.
Maritime	<i>Maritime decarbonisation strategy (DfT, 2025d)</i>	The strategy aims to achieve zero lifecycle GHG emissions from UK domestic maritime by 2050, reducing dependency on volatile fossil fuel markets and improving energy security for maritime transport.
Rail	<i>Fourth Adaptation Report, Network Rail (2024)</i>	Prioritises maintenance and climate resilience, comprehensive risk assessments, alignment with regional growth strategies, investment in infrastructure upgrades, and robust emergency response mechanisms. Existing assets and network adaptability should be improved.
	<i>Rail Resilience Project, Rail Delivery Group (2021)</i>	Industry-leading programme establishing a Code of Practice for rail sector resilience. Measures individual and organisational capabilities using KPIs and KRIs, with regular maturity assessments (aligned to ORR's RM3) to guide continuous improvement. Key principles include strong leadership, accountability, strategic alignment, horizon scanning, real-time risk monitoring, and inclusive engagement. The framework fosters evidence-based decision making, adaptable responses, and a culture of ongoing learning to help rail entities 'bounce forward' after disruption.

Road	<i>ARP4 Report, National Highways (2024a)</i>	Outlines how route resilience is integrated into long-term strategic planning. It sets out National Highways' 2050 vision, which recognises the need for key corridors within the Strategic Road Network (SRN) to be resilient to disruptive events such as climate change, flooding, and physical blockages. The report places strong emphasis on asset resilience and environmental sustainability, highlighting the role of the Environmental Sustainability Strategy (ESS) in guiding adaptation efforts. Current actions have already improved flood resilience at over 100 vulnerable locations. Looking ahead, National Highways plans to map future flood risks across the SRN under various climate change scenarios, with the aim of identifying opportunities to strengthen route-level resilience.
	<i>National Highways Climate Change and the Strategic Road Network (2024b)</i>	Emphasises the need for a policy shift towards integrating climate projections into infrastructure planning, prioritising durable asset design, nature-based solutions, and cross-sector collaboration to future-proof transport systems against extreme weather, rising temperatures, and sea level rise.
	<i>The Strategic Road Network Initial Report 2025-2030, National Highways (2025a)</i>	Positions network resilience as central to the long-term development of England's transport infrastructure, stressing the need for system-wide continuity amid climate volatility, ageing assets, and rising demand. National Highways prioritises renewing critical infrastructure, ensuring that local disruptions do not affect overall connectivity. The report highlights growing reliance on digital infrastructure, making resilience a matter of both physical and cybersecurity, data integrity, and real-time traffic management.

Whilst their higher-level strategies acknowledge the need for systemic resilience across a range of potential shocks and stresses, the published strategies to date focus predominantly on climate-related risks and adaptation measures. This has left a current gap in the strategic policy making framework relating to resilience in a transport context, which comprehensively address operational resilience, cross-modal dependencies, and long-term asset performance under non-climatic stressors. It is partially referenced through **DfT's Better Connected Strategy (2026)** and the **Third Road Investment Strategy (RIS3)** (DfT, 2026) places greater emphasis on long-term adaptation planning and investment to enhance the resilience of individual routes within the SRN. Transport resilience officials are working to provide a clearer strategic framework for transport resilience more specifically.

Several **local authorities** in the UK have developed targeted strategies to enhance network resilience across their transport systems. The *East Sussex Highway Network Resilience Plan (2025–2030)* identifies a designated Resilient Network comprising the minimum set of routes required to maintain essential connectivity, support emergency response, and sustain economic activity during disruptive events. This includes links to strategic roads, emergency facilities, and critical infrastructure such as ports and power stations. The plan applies a risk-based methodology to prioritise routes based on their strategic importance and vulnerability to hazards such as flooding, heatwaves, and industrial action. Similarly, the *Buckinghamshire Highways Resilient Network Plan (2025)* focuses on maintaining connectivity between major communities and access to emergency services, public transport, and key employment areas. The council has invested heavily in drainage infrastructure and introduced a real-time Operational Control Hub (OCH) to monitor network conditions and coordinate responses.

Professional bodies and Non-Governmental Organisations (NGOs) have also discussed the importance of resilience to the transport system, providing recommendations for policy making. For example, the **Chartered Institution of Highways & Transportation (CIHT) 'Delivering a resilient transport network' (2024)** paper highlights the importance of resilience against severe weather, physical and cyber threats, and supply chain risks. It focuses on proactive risk management, regular testing/exercising of plans, enhanced data-sharing, investment in infrastructure maintenance, and supporting interdependency awareness between transport and other sectors.

Wider Infrastructure Resilience Strategies and Policies

Transport systems form a critical part of overall UK infrastructure. UK infrastructure strategy and policy making has also increasingly addressed resilience as a core foundation – which is highly relevant to the transport system.

The UK 10 Year Infrastructure Strategy (HM Treasury, 2025) sets out the government's long-term plan to create resilient, sustainable, and interconnected infrastructure across transport, energy, water, and digital infrastructure sectors. The strategy emphasises strengthening the UK's ability to anticipate and recover from risks, embedding net zero and environmental goals into future projects and improving connectivity between infrastructure systems. It acknowledges that past infrastructure investment has been poorly coordinated, leading to vulnerabilities in systems underpinning economic productivity. To address this, the strategy commits to mapping existing resilience standards, identifying gaps, and introducing or reinforcing standards where necessary.

Specifically for transport, it calls for setting clear expectations for the resilience of key routes and nodes, and for developing forward-looking standards that account for future threats such as climate change and asset deterioration. The strategy also highlights the need to consider interdependencies between sectors, ensuring that resilience planning is not siloed but integrated across transport, energy, water, and digital infrastructure.

The Second National Infrastructure Assessment (National Infrastructure Commission, 2023) predated the Infrastructure Strategy and provided a plan for the UK's infrastructure needs over the next 30 years, focusing on supporting sustainable economic growth, improving competitiveness, quality of life, and delivering net zero by 2050. The Commission recommended that government should publish resilience standards for the digital and telecoms, energy, transport and water sectors by 2025.

Developing resilience standards in UK infrastructure (National Infrastructure Commission, 2024) sets out how government can implement the Commission's recommendation of published resilience standards. The report calls for transport networks including strategic roads, local roads, and rail to adopt forward-looking asset health standards that reflect the impacts of climate change and evolving risks. These metrics should evaluate the expected lifespan of key assets, such as road drainage, and quantify the probability of failure, thereby informing long-term maintenance and investment decisions. NIC advised that the government should develop a cross-modal, strategic approach for key transport routes and nodes, clearly identifying which must remain operational during extreme weather events and which may be safely closed, as well as ensuring viable alternatives across modes.

The report also advocates resilience policies that take account of the complex, multi-modal nature of the transport system, recognising the need to consider competition and interdependence between road, rail, maritime, and aviation, and to safeguard continuity of service for both passengers and freight during disruptions. Importantly, NIC recommended regular reviews of resilience standards and coordinated actions across government and industry to address gaps, manage trade-offs, and build system-wide resilience into future infrastructure planning and delivery.

Currently, the rail sector has made the most progress on adopting resilience standards and guidelines through Rail Delivery Group's Rail Resilience Project (2021) and its Codes of Practice and associate Tools for Resilience (2025).

UK supply chain resilience strategy and policy is also somewhat relevant to the transport context, because the supply of goods and services across critical UK supply chains requires the continued functioning of the transport system. The **Supply Chains Resilience Framework (Department for Business and Trade, 2022)** defines a framework for managing the resilience of critical supply chains, whilst the **Critical Imports and Supply Chains Strategy (Department for Business and Trade, 2024)** identified some of these critical sectors including minerals and rare earths, critical inputs for the automotive industry and healthcare and medical products.

Workforce Resilience

The Department for Transport's **Climate Adaptation Strategy for Transport (2025)** builds on the definition of resilience beyond physical infrastructure to include institutional and human dimensions. This means that the ability to withstand and adapt to climate-related risks depends not only on robust transport systems but also on the capacity of organisations and individuals within the sector to respond effectively. Workforce resilience is described as foundational to maintaining service continuity and enabling adaptive capacity. It ensures that the transport system is not only physically robust but also institutionally prepared to respond to future challenges.

Complementing this, the **Future Skills Needs Across the Transport Sector report (DfT, 2024b)** identifies critical workforce challenges that could hinder the sector’s resilience. These include an ageing workforce, persistent skills shortages, and rising demand for digital and green competencies. The report, commissioned by the DfT and produced by the **National Skills Academy for Rail (NSAR)**, stresses that without addressing these issues, the sector may struggle to adapt to rapid technological and environmental changes. It recommends a coordinated, sector-wide effort to attract and retain talent through apprenticeships, improved career pathways, and targeted upskilling initiatives. These actions aim to ensure the workforce is not only technically proficient but also adaptable to future demands.

The Transport Infrastructure Skills Strategy (DfT, 2016a) reinforces this approach by advocating for resilience to be embedded in workforce planning. It highlights the importance of diversity, inclusion, and mobility, arguing that a more representative and agile workforce is better equipped to respond to change. The strategy also anticipates technological transformations such as smart motorways and digital railways, calling for training programmes, succession planning, and cross-sector collaboration to prepare the workforce for these shifts.

2.2.2 Strategic Interventions to Improve Resilience of Transport Systems

This strategic policy backdrop highlights the wide range of potential interventions that are being considered to promote resilience of the transport system to address its priority resilience needs. These strategies span the whole of the ‘resilience cycle’ (Cabinet Office, 2023a):

Figure 3. The resilience cycle. Source: PA analysis of multiple sources, including Cabinet Office risk cycle.



Some of these interventions contribute to reducing or preventing the risk/stress and others contribute to building ‘adaptive capacity’. Field (2020) uses the terms mitigation and adaptive capacity to distinguish between preventative actions and those needed to adapt or recover from incidents. Each resilience strategy is explained in more detail below:

Table 5: Strategies for delivering resilience in a transport context.

Resilience strategies that target risk reduction		Transport example
Prevention	Risks can be prevented by taking steps to eliminate the threat, hazard or the likelihood of occurrence.	Land use planning to avoid building railway lines in flood-prone areas.
Preparedness	Developing policies, plans and processes to manage risk and testing them for effectiveness in a safe environment.	Regular emergency simulations of risks across rail networks such as fires to prepare staff and systems for safety procedures in the case of real incidents.

Robustness ('Mitigate')	Taking proactive steps to reduce the impact of a risk, typically through reducing the vulnerability of the system by improving its strength to withstand specific risks.	Elevating road surfaces and reinforcing bridges to withstand extreme weather events such as flooding or storms.
Redundancy ('Mitigate')	Add components which are not necessary to functioning, in case of failure in other components. This intervention could be agnostic of the risk.	Deploying alternative transport arrangements to key energy infrastructure, so that supplies can be re-routed to ensure continuity if there is an interruption.
Fail-safe ('Mitigate')²	Implement measures to ensure that any failure is proportionate and does not propagate within the system or instigate other undesirable events. This intervention could be agnostic of the risk.	Automatic Train Protection (ATP) systems on UK railways stop trains if signals are passed at danger, preventing collisions and cascading failures.
Resilience strategies that build adaptive capacity		Transport example
Anticipate	Provide situational awareness through monitoring systems to identify changes in system demand/capacity; conduct trend analysis or scenario planning. (This intervention can be targeted at specific risks).	Monitoring cyber security risks to transport bodies through the National Cyber Security Centre (NCSC) monitoring function, which detects and analyses UK cyber security events.
Respond	If incidents do occur, good coordination, communication, leadership and decision-making can deliver a more effective response, reducing disruption and potentially reducing recovery time. Resourceful systems often respond better.	Airport incident response teams coordinating with air traffic control and emergency services to manage runway closures or aircraft emergencies efficiently.
Adapt	Build ability to easily upgrade or change systems; adapt to the situation by providing flexibility in processes, people and solutions.	Designing bus networks with flexible routing options and changing scheduling to allow quick adjustments during service disruptions or major events.
Recover	Good coordination, communication, leadership and planning can enable quicker recovery from disruption.	Implementing post-incident recovery plans to restore services after a disruption, including rapid infrastructure assessments and phased service resumption.
Learn and transform	Develop methods to capture evidence, learning and innovation – learning from own and others' actions to improve readiness for future potential crises. This should feed into the application of all resilience strategies and reduce future risk. Innovate to transform the system to 'bounce forward' to an improved level of functionality.	Using post-incident reviews of major traffic accidents to inform updates of highway design standards and emergency response procedures.

These interventions are linked to the scope of the economic appraisal and the option identification, long-listing and short-listing process, which is discussed in more detail in Section 3.5.1.

2.2.3 Key Themes Underpinning the TAG Appraisal Framework

It is important that the key themes underpinning the evolution of strategic policy making underpin the TAG appraisal framework – so that the economic analysis is aligned to the most important strategic objectives of resilience policy and fulfils the strategic need from decision-makers. Key takeaways for the design of the appraisal framework that are taken forward as part of the Conceptual Framework include:

² Although redundancy and fail-safe strategies are closely related, they serve distinct purposes. While both aim to mitigate risk, redundancy provides alternative components or pathways to maintain functionality if one element fails, whereas fail-safe measures ensure that any failure remains contained and does not escalate into wider system disruption.

- **Applicability to a wide variety of resilience interventions:** a variety of interventions are identified across strategic policy documentation, ranging from hard infrastructure to adaptive capacity. The framework should be able to consider and compare these different types of interventions as part of the appraisal.
- **Recognising interdependency across transport system and wider systems:** the significant interdependencies highlighted between the transport systems and broader infrastructure and energy systems and the wider economy, demonstrate the need to capture the knock-on impacts beyond the initial impacts on transport users (addressed further in Section 2.3),
- **Agnostic to different forms of risk:** Policy is increasingly recognising that future shocks and stresses may emerge from unpredictable sources. Flexibility in the appraisal framework will be necessary to capture both predictable chronic stresses (such as climate change) and less predictable acute shocks, as well as new and emerging trends (for example, the potential impact of AI). The framework should also support the appraisal of programmes that proactively address these changes, such as initiatives to upskill transport sector workers. Proportionality will ensure effort is guided towards the most consequential potential risks and opportunities.
- **Dynamic framework:** The constantly changing nature of the risks set out in policy means that existing assumptions underpinning appraisals may need to be rapidly updated to reflect emerging evidence on evolving vulnerabilities – calling for a dynamic rather than static framework.
- **Identifying the role for resilience standards:** whilst not currently implemented in transport, the growing emphasis on resilience standards means it is important to recognise how these would be accommodated in the framework moving forward.

Key Findings

- The UK Government Resilience Framework establishes **foundational principles** for transport resilience: comprehensive risk understanding, proactive prevention, and engaging all sectors of society. Transport is recognised as **Critical National Infrastructure** essential to national security and economic stability.
- The UK Resilience Action Plan applies these principles, focusing on ongoing **risk assessment, enabling collective action, and strengthening public sector systems**. Transport-specific measures include improved risk data, investment in resilient infrastructure, operator preparedness, and regular emergency plan testing.
- The Cabinet Office emphasises a “**whole-of-society**” approach, calling for coordinated efforts across government, industry, and communities, including improved risk assessment, data sharing, investment in resilient infrastructure, and regular emergency response exercises for transport networks.
- DfT and transport bodies develop **sector-specific security and resilience plans**, emphasising asset protection, risk mitigation (including cyber threats), service continuity, and cross-government collaboration. Recent initiatives focus on climate adaptation, scenario testing, and integrating resilience into routine operations.
- Recent consultations and reports highlight a shift towards mainstreaming **climate adaptation and resilience** into investment and operational decisions, requiring collaborative cross-sector strategies and improved data and methods to address systemic risks and interdependencies.
- Mode-specific resilience strategies (aviation, maritime, rail, road) **prioritise adaptation, durable design, energy security, and coordinated emergency response**, but published policies mostly address climate risks, leaving gaps in operational and cross-modal resilience, with the notable exception of the rail sector’s Rail Resilience Project.
- Broader infrastructure policies **call for resilient, integrated systems** supported by national standards, regularly updated and cross-sectoral, to support transport continuity during disruptions.
- **Supply chain resilience strategies** are linked to transport, recognising its role in supporting uninterrupted flows of critical goods and services.
- **Key themes** for evolving the TAG appraisal framework include flexibility to assess a range of interventions, modelling dynamic interdependencies, accommodating diverse risk types, adapting to emerging evidence, and preparing for the inclusion of resilience standards. This alignment supports robust, strategic decision-making in transport resilience planning.

2.3 Key Acute and Chronic Risks to the Transport System

This section explores the evolving risk landscape, identifying the most relevant and material acute and chronic risks impacting the UK transport system. It aims to inform the appraisal framework through identifying the types of risks that might have the biggest impacts on resilience impacts and should be factored into the appraisal. In this section we address the following research question:

Key research question: *What are the most relevant and material acute and chronic risks that impact resilience in a transport context?*

2.3.1 Risk and Uncertainty

In the UK, The Green Book defines **risk** as:



Risk: “specific uncertainties that arise from activities such as forecasting or implementation, the costs of which have been estimated. They are specific to an intervention and may be quantified and managed”. (HM Treasury, 2022)

ISO’s (2021) definition of risk aligns to this – “the effect of uncertainty on objectives.” Risks can be assigned to 3 main categories which are not mutually exclusive: business, service and external risks.

- **Business risk:** The risk an organisation fails to deliver its commitments and cannot meet its business objectives
- **Service risks:** The risk a service is not fit for purpose
- **External Risk:** The risks that are not connected to the proposal being considered.

The type of risks most relevant to resilience are external risks impacting upon the organisation, but risks may also emanate through failures in the service or business itself. The National Risk Register (NRR), last updated in January 2025, is the public-facing version of the UK government’s National Security Risk Assessment (NSRA), which identifies the most serious external risks to the UK and its interests. It outlines the likelihood and potential impact of a wide range of risks and is intended for use by risk and resilience professionals, including in transport bodies. This is formalised in the risk equation:

$$\text{Risk} = \text{Likelihood} \times \text{Impact}$$

The risks that meet the threshold for inclusion in the NRR would have a substantial impact on the UK’s safety, security and/or critical systems at a national level. The NRR currently contains 89 acute risks across nine risk themes: accidents and systems failures, animal and plant health, conflict and instability, cyber, geographic and diplomatic, human, natural and environmental hazards, societal, state threats, and terrorism. Departments are asked to consider how acute and chronic risks interact, as chronic risks can increase the likelihood or impact of acute risks.

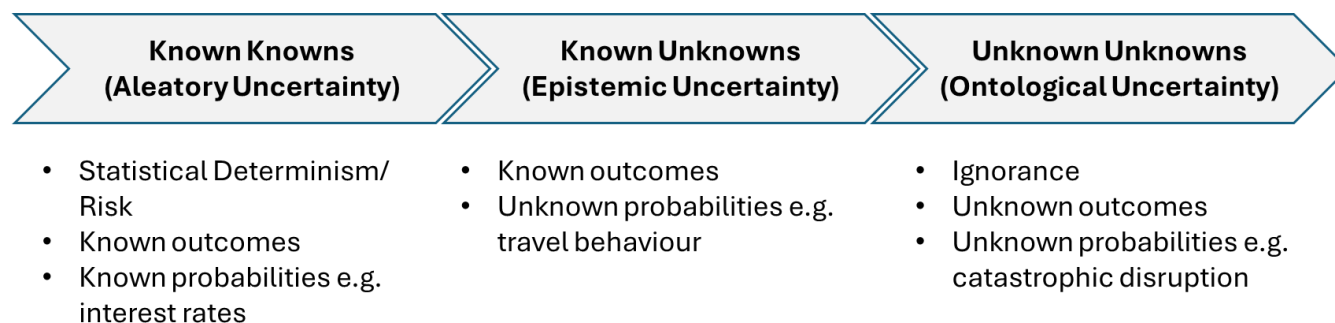
Unlike risk where there is a likelihood of a specific outcome, **uncertainty** refers to a condition where future events are unknown. The TAG Uncertainty Toolkit (2025j) explains how risk is, to an extent, controllable and can be mitigated through thorough planning and intervention where necessary whereas, control and mitigation in the traditional sense is unviable for general uncertainty. It broadly defines uncertainty as:



Uncertainty: “limited knowledge about past, current and future events and the systems in which these events occur.” (DfT, 2025j)

There are three key classifications of uncertainty:

Figure 4. The Classification of Uncertainties. Source: DfT



DfT's Climate Risk Assessment Guidance for the Transport Sector (2025I) highlight that some risks are less certain than others. For example, projections for how precipitation will change in the future are less certain than projections for how average temperatures will change. In the context of decision-making relevant to this review, uncertainty is referred to as the gap between available knowledge and the knowledge decision makers would need to make the best, most informed policy decision.

Kay and King (2021) coined the term "*radical uncertainty*" to reflect the growing incidence of unknown unknowns. In resilience, although the potential disruption may not be known, capacity would still need to be built to protect the system from these unknowns through an understanding of system vulnerabilities and criticalities.

2.3.2 Distinguishing Risks, Threats and Vulnerabilities

When examining the risk landscape, it is first important to disentangle the three core components of 'risk': threats/hazards, exposure and vulnerability. The Coalition for Disaster Resilient Infrastructure (CDRI) defined these factors in their Global Infrastructure Risk Model and Resilience Index (GIRI) as:

- **Threats/hazards:** The external threat or shock event (e.g. flood, cyberattack)
- **Exposure:** The presence of people, assets, or systems in harm's way
- **Vulnerability:** The susceptibility of those exposed systems to suffer damage or disruption

This built on initial work from Pregnotato and Dawson (2018) who identified the interplay between these three foundational elements as critical for assessing how infrastructure systems respond to disruptions. ISO also provides definitions for threats and vulnerabilities:



Threat: "potential cause of an unwanted incident which could result in harm to individuals, assets, a system or organization, the environment or the community." (ISO, 2021)

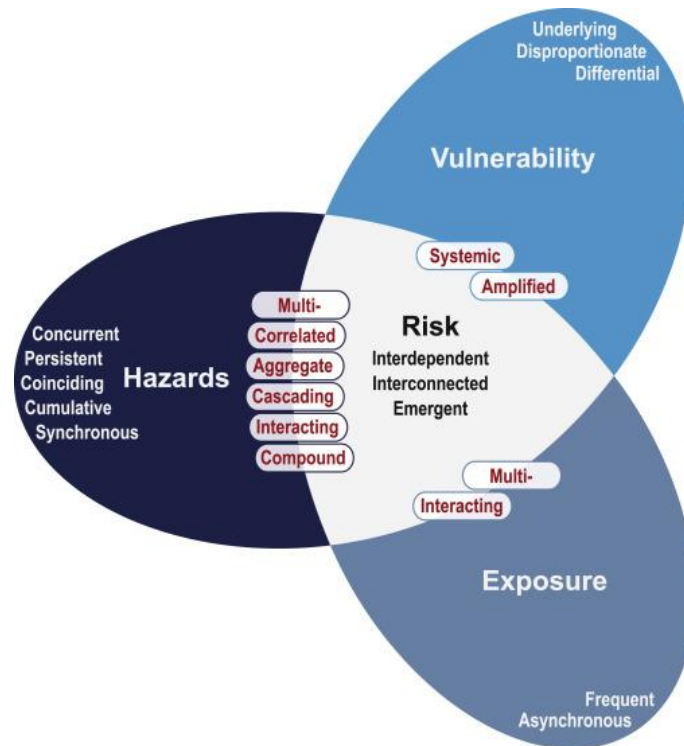
Vulnerability: "weakness of an asset or control that can be exploited by one or more threats." (ISO, 2018)

Unlike an immediate hazard, vulnerability can accumulate and prevail over time and is intricately linked to the level of social and economic development of exposed communities. The importance of also understanding the exposure and vulnerability, rather than solely the immediate hazard, is further emphasised in the European Climate Risk Assessment (European Environment Agency, 2024), which notes that "*climate risks to ecosystems, people and the economy depend on non-climatic risk drivers as much as on the climate-related hazards themselves.*"

This aligns with the conceptual framework presented by Simpson et. al. (2021) which presents risk in the context of climate change as the result of the interaction between hazards, exposure and vulnerability. Figure 5 illustrates how these dimensions intersect to produce complex and interconnected risks. This model encourages a shift from siloed risk assessments towards integrated, systems-based approaches. **Hazards** are characterised by both intensity and spatial patterns including concurrent and cumulative events. **Exposure** relates to the frequency and distribution of assets and populations in harm's way and **vulnerability** captures the underlying structural and social conditions influencing susceptibility to damage.

This highlights how risks impacting the transport system are not solely determined by the external threat, but also by the degree of exposure to transports users and affected communities, and the underlying vulnerabilities present across transport systems.

Figure 5. The diversity of complex climate change risk terminology. Source: Simpson et. al. (2021)



2.3.3 Demand and Supply-Side Risks

Risks can emanate from the demand or the supply side, or a combination of both. **Supply side risks** impact the **provision of transport services**. These risks can include ageing or poorly maintained infrastructure, fuel supply interruptions, labour shortages (such as HGV drivers or rail staff), and technical failures in vehicles or control systems. External shocks like cyber-attacks, extreme weather, or industrial action can severely impact provision of transport services and can lead to reduced capacity of the transport system.

On the other hand, **demand-side risks** impact an **individual's use of the transport system**. Sudden behavioural shifts can lead to unexpected changes in use of the transport system. For example, demand for rail services fell abruptly following public health measures announced in response to Covid-19. Annual UK rail passenger volumes fell from 1.7bn in 2019 to 0.4bn in 2020 (Office of Rail and Road, 2020). Another example would be the fall in the demand for air travel following the 9/11 terrorist attacks – UK air travel fell by 6% in December 2001 compared to a year prior (BBC News, 2002).

While demand for rail has now fully recovered (ORR, 2025), in 2024 it was still around 8% below its pre-pandemic peak (DfT, 2024c), highlighting how demand-side shocks can also **feed through into longer-term behavioural changes** and potentially evolve into chronic risks. For example, remote working patterns have shifted how people choose to travel and their preferences for active travel modes (Allanfield Consulting, 2023). Long-term demographic trends can shape demand-side chronic risks in a similar way. For example, ageing populations may reduce commuting demand while increasing accessibility needs. And urbanisation can concentrate demand in cities, while rural areas may face declining usage, affecting service viability.

Larcom et. al. (2017) examined these long-term behavioural responses following the central line closure in February 2014 due to London Underground strikes. Their analysis found that many London commuters were using inefficient routes because they didn't have full information. However, the disruption forced them to try new routes, and some found better ones that they continued to use after the disruption had ended. This suggested that transport users often stick to habits and don't explore other options unless it is necessary (i.e. during a shock event), challenging the assumption of rational, optimising behaviour.

2.3.4 Defining Acute and Chronic risks

The resilience of the transport system is shaped by a dynamic and increasingly complex risk environment. As outlined in Section 2.2, these risks are either acute or chronic in nature, defined as:



Acute risk: “discrete events that usually require an immediate response” (Department for Transport, 2025c)

Chronic risk: “continuous challenges which gradually erode our economy, community, way of life and/or national security” (Department for Transport, 2025c)

Acute risks can cause **sudden and severe disruption to the transport system**. These include extreme weather events (such as storms, flooding, and snow), pandemics, and major accidents. Alternatively, these can be intentional such as by protests. Acute risks are often high-impact but low-probability, requiring robust emergency preparedness and rapid response capabilities. In contrast, chronic risks develop gradually and **exert sustained pressure on the transport system**. These can include rising temperature and sea level due to climate change, ageing infrastructure, demographic shifts, and behavioural changes. These both degrade the day-to-day performance of transport systems as well as exacerbating the impact of acute shocks.

It is possible to further distinguish these risks using the Simpson et al (2021) framework: acute risks are typically associated with hazard events interacting with exposed and vulnerable systems. In contrast, chronic risks are influenced by persistent vulnerabilities and long-term exposure patterns.

DfT’s ‘Transport Hazard Summary: Risks and Resilience’ paper (2025c) further differentiates between hazards and threats as sources of acute risk. A hazard is described as a:



Hazard: “non-malicious event that is dangerous and likely to cause damage” (Department for Transport, 2025c)

This includes extreme weather, accidents or the natural outbreak of disease. Threats, by contrast include malicious events such as terrorism (e.g. the 1992 Staples Corner bombing), espionage and cyber-attacks which may target CNI or key protective agencies such as the NPSA (National Protective Security Authority) or NCNC (National Cyber Security Centre).

2.3.5 Acute Risks in a Transport Context

The National Security Risk Assessment (NSRA), which underpins the **National Risk Register (NRR)** (HM Government, 2025), provides a comprehensive and continuously updated view of national risks. As discussed in Section 2.3.1, the 2025 edition of the NRR identifies 89 acute risks across nine themes, all of which are relevant to transport systems, including:

- **Cyber-attacks** on the transport sector, including rail, aviation, and maritime systems, which could disable control systems, disrupt logistics, or compromise safety
- **Malicious incidents**, such as terrorist attacks on rail or aviation infrastructure, or the use of drones to disrupt airspace
- **Major transport accidents**, including rail collisions, aviation incidents, or maritime accidents involving large passenger vessels or hazardous cargo
- **Severe weather events**, such as storms, flooding, or snow, which can cause widespread disruption to road, rail, and air networks
- **Fuel supply disruptions**, whether due to industrial action, cyberattacks, or infrastructure failure, which can paralyse transport operations.

Any of these risks could cause multiple points of failure across the transport system for a relatively short period, severely disrupting mobility of both people and goods across specific routes and the broader network. Catastrophic events (defined in the NRR as resulting in more than 1,000 fatalities, more than 2,000 casualties and/or costing tens of billions of pounds), such as widespread major flooding or coordinated cyber-attacks, could cause widespread and prolonged failure of the transport system at a national level. DfT’s *Transport Hazard Summary: Risks and Resilience* (2025c) paper highlights how these events can damage infrastructure, disrupt services, and pose risks to life, safety, and economic continuity.

Matsson and Jenelius (2015) outline a typology of acute risks to transport systems according to the nature of its causes:

Table 6. Typology of key risks to transport sources. Source: Matsson and Jenelius (2015)

Causes	Accidental	Intentional
Internal	Technical, operational, human failure	Strikes
External	Climate events, pandemics	Geopolitical tensions, terrorism, cyber-attacks

Cyber-attacks and wider cyber security risks have emerged as a critical acute risk area in recent years. As transport systems become more digitised and reliant on real-time data, they are increasingly vulnerable to cyber-attacks or technology failures (see [Case Study 2](#)). The Integrated Review Refresh (HM Government, 2023) and the Critical Imports and Supply Chains Strategy (Department for Business and Trade, 2024) both emphasise the growing threat of digital disruption to transport and logistics, particularly in the context of geopolitical instability. Reliance on digital platforms for travel planning, freight coordination, and infrastructure management has introduced new points of failure.

Case Study 2
National Air Traffic Services (NATS) System Failure – August 2023

On August 28, 2023, a technical failure in the UK’s National Air Traffic Services’ flight planning system forced the restriction of aircraft numbers across UK airspace for over seven hours. Hundreds of flights were delayed or cancelled, stranding tens of thousands of passengers at airports including Heathrow, Gatwick, Manchester, and Edinburgh (Image 3).

Airlines struggled to recover schedules for several days. The subsequent investigation found the root cause to be a rare data processing fault which was not detected by existing safety checks. The event highlighted both the complexity and the vulnerability of national air traffic control infrastructure and sparked calls for further investment in system resilience and real-time fault detection.

Image 2. Many passengers were delayed by the NATS failure, including at Gatwick airport.



[This photo](#) by Unknown Author is licensed under [CC BY-NC 4.0](#)

Source: [NATS August 2023 system failure review | UK Civil Aviation Authority](#)

Severe weather events are increasingly recognised as a major acute risk to transport systems in the United Kingdom (see Case Studies below).

The National Risk Register (NRR) also identifies **surface water flooding and high winds** as particularly disruptive to road and rail networks, with the potential to compromise transport user safety, disrupt economic activity, and complicate emergency response efforts. Severe weather can lead to extended closures, service delays, and increased maintenance demands, reinforcing the need for robust mitigation and adaptation strategies across all modes of transport.

Case Study 3

Carmont (Stonehaven) Derailment, 2020

In August 2020, a fatal rail accident occurred near Stonehaven, Scotland, when a passenger train derailed following a debris flow caused by intense rainfall during a 1-in-100 to 1-in-144-year storm event (Image 3).

The incident was linked to drainage infrastructure installed in 2011 that had not been built in accordance with its design specifications. The derailment resulted in the deaths of three people and injuries to six others. The line was closed for approximately three months, causing significant disruption to rail services in the region. The event highlighted critical vulnerabilities in infrastructure resilience, particularly in the face of increasingly frequent extreme weather events, showing the importance of robust maintenance and climate adaptative design of transport systems.

Image 3. Train derailment at Carmont.



[This photo](#) by Unknown Author, appearing in RAIB report "[Derailment of a passenger train at Carmont, Aberdeenshire](#)" is Crown Copyright.

Source: [Report 02/2022: Derailment of a passenger train at Carmont - GOV.UK](#)

Case Study 4

A591 (Cumbria) Landslides, 2015

In 2015, the A591 road in Cumbria experienced multiple landslides and embankment failures following a single, intense rainfall event. The affected embankments had been constructed in the 1880s, prior to the establishment of modern engineering standards, making them particularly vulnerable to extreme weather. The disruption led to the closure of the road for five months, severing access to key services including schools and isolating communities. The economic impact was substantial, with losses estimated at £1million per day due to interrupted travel, reduced business activity, and delayed logistics.

Image 4. Partially collapsed section of road on the A591 during Storm Desmond.



This still "from [YouTube video](#) "THIRLMERE SIMON Q&A" by Cumbria County Council is licensed under [CC BY 2.0 DEED](#)

Source: '[Scenes of devastation](#)' on flood-hit A591 through Lakes - BBC News

Public health emergencies, such as the COVID-19 pandemic, have further demonstrated the vulnerability of transport systems to acute shocks. The National Risk Register rates pandemics as a severe acute risk (see [Case Study 5](#)). These shocks can lead to dramatic shifts in travel behaviour, reduced demand, and disruptions to supply chains. Transport bodies can also be required to rapidly deploy a range of health-related interventions to manage public health risk, including providing more active travel options and non-pharmaceutical measures like enhanced surface cleaning, installation of barrier screens, and implementation of travel restrictions (International Transport Forum, 2023).

Case Study 5

The COVID-19 Pandemic – Global Transport Disruption, 2020-2021

The COVID-19 pandemic was a key event exposing the vulnerability of transport systems to biosecurity risks. From early 2020, the rapid international spread of SARS-CoV-2 was enabled by global travel networks, leading to widescale infection and prompting countries to implement unprecedented travel restrictions. Borders were closed, quarantine measures and mandatory testing were enforced for travellers, and mask mandates were introduced across transport modes (Image 5). Transport operations worldwide were severely disrupted: aviation, rail, road, and maritime sectors all saw dramatic declines in passenger volumes and shifting patterns of demand. The sudden changes revealed the difficulty of adapting schedules, reconfiguring networks, and managing supply chain disruptions amidst evolving public health directives.

The pandemic highlighted the critical need for biosecurity and pandemic preparedness within transport resilience planning. In response, governments have enacted more integrated health surveillance and promoted greater flexibility in transport operations. Transport resilience planning has also been re-evaluated, with greater emphasis on adaptability and continuity under stress.

Image 5. Masks became mandatory on all public transport in England on June 15, 2020.



Source: [Mega-disruptions and policy change: Lessons from the mobility sector in response to the Covid-19 pandemic in the UK](#)

The Impacts from Acute Risks Materialising

Across these examples of acute risks, wide-ranging negative impacts have been observed from acute risks impacting the transport system:

- **Safety of people:** Risks include injury or death to road users, public transport staff, emergency responders, and clean-up crews.
- **Transport performance:** Closures impacting transport users, with the degree of disruption driven by traffic levels and alternative route capacity.
- **Environmental impacts:** Diversions and mode shifts can increase emissions and energy use; ecosystems may be harmed and pollutants spread.
- **Infrastructure and property damage:** Damage to transport assets and nearby infrastructure, requiring repairs, or potentially new structure renewals or enhancements.
- **Social impacts:** Disruptions can limit access to essential services, reduce community connectivity, and contribute to stress and isolation, especially in vulnerable groups.
- **Economic impacts:** Costs span immediate response and repair, longer-term travel inefficiencies, and broader economic losses, particularly in rural or tourism-dependent areas.

These impacts are further examined through the TAG appraisal framework in Section 3. DfT's *Transport Hazards, Risk and Resilience (2025c)* highlights how impacts on the transport system can be 'direct' in nature – directly resulting from the shock – or 'indirect' – transmitted to the transport system through interdependencies with other systems. Table 7 provides examples on how an acute risks can lead to both types of impact:

Table 7. Selected acute risks and impacts on transport systems. Source: PA Consulting analysis

Acute risk	Description	Direct impact on transport	Indirect impact on transport
Pandemic	Widespread infectious disease outbreak affecting population health and mobility	Reduced passenger demand, service suspensions, workforce shortages	Supply chain delays, economic slowdown, long-term shifts in travel behaviour (e.g. remote work)
Extreme heat	Prolonged periods of unusually high temperatures	Rail buckling, road surface damage, vehicle overheating, speed restrictions	Increased maintenance costs, reduced reliability, health risks for passengers and staff
Severe space weather	Solar storms disrupting satellite and communication systems	GPS and navigation failures, signal blackouts,	Disruption to logistics and digital infrastructure

		disruption to air and rail operations	
Surface water flooding	Intense rainfall overwhelming drainage systems	Road and rail closures, vehicle damage, infrastructure erosion	Disruption to commuting and freight, increased insurance and repair costs
Coastal flooding	Sea level rise or storm surges inundating coastal infrastructure	Damage to ports, coastal roads and rail lines, service suspensions	Disruption to trade and supply chains, long-term relocation or redesign of infrastructure

2.3.6 Chronic Risks in a Transport Context

Unlike acute risks, which are sudden and disruptive, chronic risks are long-term, evolving threats that gradually degrade the resilience and performance of transport systems. These risks accumulate over time, often going unnoticed until they significantly undermine infrastructure performance, operational capacity or economic stability. The Cabinet Office Resilience Action Plan (2025a) highlights how technological advances, while enabling greater connectivity, have also introduced **systemic vulnerabilities** through reliance on digital platforms and global supply chains. The Chronic Risks Analysis (CRA), Cabinet Office (2025b), further emphasises that chronic risks are often **interconnected, with compounding effects** that can erode resilience across critical systems. This complexity demands a more integrated and forward-looking approach to risk management in transport planning.

Chronic risks can also increase the likelihood or severity of acute events or reinforce other chronic risks, and their impacts are often difficult to reverse. For example, whilst a landslide itself is an acute risk, it is often triggered by longer-term patterns in rainfall or coastal erosion. The likelihood and severity of landslides are influenced by chronic risks such as climate change (rainfall duration and intensity), land use changes (e.g. deforestation, construction) and geological conditions.

The NSRA mapped 7 themes and their drivers of chronic risk, shown in Table 8 below:

Table 8. Selected drivers of chronic risk. Source: Cabinet Office (2023b)

Theme	Drivers of chronic risk
Security	Changes in the nature of terrorism
Technology and cybersecurity	Impacts from use and capability of artificial intelligence
Geopolitical	Hostile state threats
Environmental	Long-term shifts due to climate change (e.g., rising temperatures, rising sea levels, and resource scarcity)
Societal	Impacts from demographic change and workforce rigidities
Biosecurity	Antimicrobial resistance
Economic	Impacts from reliance on global supply chains

Case studies 6 and 7 illustrate how these chronic risks can impact the transport system, below:

Case Study 6

UK Lorry Driver Shortage – 2021

The UK lorry driver shortage, beginning in 2021, exposed vulnerabilities within the domestic logistics and transport sector, illustrating the chronic risk posed by the legacy of the pandemic (halted HGV driving tests and disrupted training), demographic change (retiring workers), and shifting socioeconomic demands (Brexit and the migration of non-UK drivers out of the UK).

Between 2019 and 2021, an ageing workforce and low rates of new entrants meant led to a reduction of around 45,000 HGV drivers in the UK, with almost half of UK Heavy Goods Vehicle (HGV) drivers

over the age of 50. The return of EU HGV drivers following EU Exit and pandemic-era border restrictions, and associated delays to HGV testing and licensing compounded these shortages.

From 2020, COVID-19 pandemic also exacerbated the pre-existing lorry (HGV) driver shortage by halting HGV driving tests, disrupting training, and causing many non-UK drivers to leave and not return. This, combined with EU Exit, retiring workers, and poor industry conditions, led to a significant drop in the number of available drivers and ongoing supply chain issue.

Workforce scarcity drove up costs throughout supply chains, same-day delivery prices spiked by 30% and some manufacturers and retailers, including some fuel stations, faced material shortages (Image 6). Retailers substantially increased pay and bonuses to attract drivers, and a temporary visa scheme temporary visa schemes and relaxation of working hours rules helped to stabilise the market.

Image 6. Empty shelves were seen in supermarkets across the UK in 2021 due to the lorry driver shortage.



This photo by citytransportinfo is licensed under [CC0 1.0](#).

Source: [UK government action to reduce the HGV driver shortage - GOV.UK](#)

Case Study 7

Hammersmith Bridge Emergency Closures 2019 - 2025

The ongoing closure of Hammersmith Bridge in London (Image 7) illustrates the chronic risk posed by ageing transport infrastructure. Hammersmith Bridge, a vital crossing over the River Thames, first opened in 1887. By the late 2010s, decades of deferred maintenance had left the structure vulnerable. In April 2019, fractures were discovered in the bridge's pedestals, prompting an emergency closure to motor vehicles. Despite reopening to pedestrians and cyclists, further inspections in August 2020 identified worsening cracks, forcing a complete shutdown, including to river traffic beneath the span.

The closures led to widespread disruption for commuters, emergency services, and local businesses, highlighting how ageing infrastructure can suddenly escalate into acute transport failures and undermine the resilience of urban transport networks.

Image 7. Hammersmith Bridge in London.



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Source: [Hammersmith Bridge updates - GOV.UK](#)

As the UK Government Resilience Framework (2023) and the NSRA highlight, chronic risks often interact with acute risks either by increasing their probability or amplifying their impact (such as reducing the system's capacity to respond effectively). For example, ageing infrastructure may be more likely to fail during a flood, or workforce shortages may hinder the response to a cyber-attack. Transport infrastructure is particularly highly exposed to climate and weather risks (Pregolato and Dawson, 2018).

The Rail Delivery Group identifies "trends" such as population growth, demographic change, and evolving land use as **long-term systemic forces** that shape the broader risk environment, making them distinct from chronic risks, which are threat-based. Trends influence how risks evolve and interact but may not themselves be direct risk events; rather, they act as underlying drivers that can increase vulnerability or alter the impacts of chronic risks over time. A key chronic risk arises from much greater levels of traffic using transport infrastructure assets (e.g. bridges) than was envisaged when assets were designed and built due to population growth. The impact of this greater usage than planned can then be compounded by climate change impacts.

2.3.7 The Changing Risk Landscape

In this sub-section we draw out three key observations from the literature about the changing nature of the risk landscape impacting the transport system: risks are becoming more frequent and severe, risks are more likely to 'cascade' from other sectors and risks are more interconnected across geographies.

More Frequent and Severe Risks

The nature and size of the risks facing the transport system is constantly evolving. As the UK Government Resilience Action Plan (2025) notes, the UK is experiencing a period of profound change, with climate-driven weather extremes, cyber threats, and geopolitical instability all testing the resilience of transport infrastructure.

Acute risks driven by climate change, for example, is leading to **more frequent and severe** extreme weather events such as flooding, heatwaves and storms (World Economic Forum, 2025). As extreme weather becomes more common, this may cast doubt on some of the baseline assumptions used in transport planning. For instance, traditional transport planning often assumes historical climate patterns when setting design standards for roads, rail, and drainage systems. However, projections indicate UK winters could be up to 30% wetter and summers up to 60% drier by 2070, which challenges assumptions about flood frequency, heat-related rail buckling, and pavement durability (DfT 2024c).

Furthermore, increasing technological progress and dependency across the transport system is leading to **new risks emerging** such as cyber-attacks that were less of a consideration 20 years ago. Between September 2023 and August 2024, the National Cyber Security Centre informed 542 organisations of cyber incidents affecting them, more than double the 258 reported the previous year. Of these incidents, 89 were nationally significant and 12 were classified as severe, a threefold increase in high-impact

incidents on 2022/23. The increased use of connected and autonomous vehicles present new risks for road users specifically, in that over time increasing numbers of vehicles will be dependent on systems rather than humans increasing exposure to these risks. Johansson et al. (2024) find that the proliferation of connected, automated and electrified transport technologies is significantly increasing transport system exposure to cyberattacks and related threats, with half of all reviewed papers published since 2023 – a signal of a sharply accelerating risk landscape.

Cascading Risks from Other Sectors

Risks are **increasingly interconnected**, with disruptions in one sector such as energy or health cascading into the transport system, and vice versa. The UK Resilience Action Plan, Cabinet Office (2025a) outlines how *“our lives are increasingly dependent on technology; a globally connected economy and services and infrastructure that are intertwined between public and private sectors.”*

Transport can act as both **a critical enabler as well as a point of failure** within the broader economic system as risks become increasingly systemic. For example, a cyber-attack on the energy grid can negatively impact electric rail services or a health emergency could reduce the labour force availability of public transport drivers. In contrast, **mitigations in other sectors** can significantly enhance transport resilience by reducing vulnerabilities and preventing cascading failures. For example, environmental interventions such as upstream flood defences would also protect downstream transport corridors from future flooding.

Simpson et al (2021) also define the increasingly **compounding and cascading nature of risk**, describing how multiple factors can interact and accentuate impacts across systems. This model is particularly valuable for resilience planning, as it highlights the need to address not only individual risk components but also their interactions and systemic consequences.

Case Study 8

North Hyde Substation Fire – March 2025

The Resilience Action Plan (2025) stresses the importance of mapping these interdependencies and planning for cross-sector coordination to reduce this potential impact. It uses the example of the North Hyde Substation fire, which occurred on March 20, 2025, at National Grid Electricity Transmission’s 275kV substation in west London (Image 8).

This led to a major fire and a widespread power outage which resulted in the closure of Heathrow airport, Europe’s busiest airport, for most of March 21st affecting over 1,300 flights and disruptions for days after the event. The outage also affected more than 63,000 homes, and about 150 people were evacuated from nearby properties. The incident exposed gaps in asset management and organisational decision-making, demonstrating the importance of resilience across CNI.

Image 8. Fire at North Hyde Substation in 2025.



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Source: [NESO review into the North Hyde Substation outage: terms of reference - GOV.UK](#)

Cascading Risks from Other Nations

As **global economies become increasingly interconnected** through trade, finance, and digital infrastructure, the transport sector faces growing exposure to risks which originate beyond national borders. These risks often cascade through supply chains and international trade, amplifying local vulnerabilities and creating challenges that are difficult to predict or contain. The UK's 2025 Trade Strategy (DBT, 2025) states, “*Our reliance on global supply chains, foreign investments, and overseas markets is crucial for growth but also exposes us to threats.*”

An example of how internationally driven disruptions can cascade into domestic transport challenges is presented in [Case Study 9](#), outlining the cascading impacts of the Air Traffic Control (ATC) strikes across Europe.

Case Study 9

Cascading Risks of Air Traffic Control (ATC) Strikes in Europe

Strikes by Air Traffic Controllers across Europe has emerged as a major source of transport disruption in the UK, highlighting the interconnected vulnerability of global airspace.

In the 2010's Europe experienced numerous ATC strikes. In 2016 alone, there were 22 separate strikes encompassing 41 days of direct industrial action, causing widespread disruptions that extended beyond national borders. Owing to Europe's highly integrated airspace, these strikes did not just affect flights to and from the striking nation; they also disrupted 'overflights', including those between the UK and destinations in Spain, Italy, Greece, and beyond. During the major French ATC strikes, for example, airlines including Ryanair and EasyJet were forced to cancel hundreds of flights, resulting in tens of thousands of stranded or delayed passengers and a significant adverse economic impact.

The cumulative negative effect on EU GDP between 2010 and 2015 has been estimated at €10.4 billion, with 143,000 jobs lost or not created. Most of this impact was felt through reduced inbound tourism and productivity losses, as flight cancellations and delays deter travel and lead to cancelled holidays and business trips. Airlines lost revenue opportunities, while businesses dependent on air cargo suffered knock-on disruptions to imports and exports and supply chain delays (Image 9).

Image 9. A national strike to demand higher pay paralysed airports, seaports and rail traffic in Belgium in 2019. There were almost no flights landing at or departing from Belgian airports during the strike since air traffic controllers could not guarantee safety with a skeleton staff.



This Photo by Unknown Author is licensed under [CC BY](#)

Source: [a4e-study-pwc-economic-impact-of-air-traffic-control-strikes-in-europe-2016-09-26.pdf](#)

Internationally, the World Economic Forum published a Global Risk Report (2025) highlighting how both acute and chronic risks are creating an increasingly fragmented global landscape. The report defines global risk as:

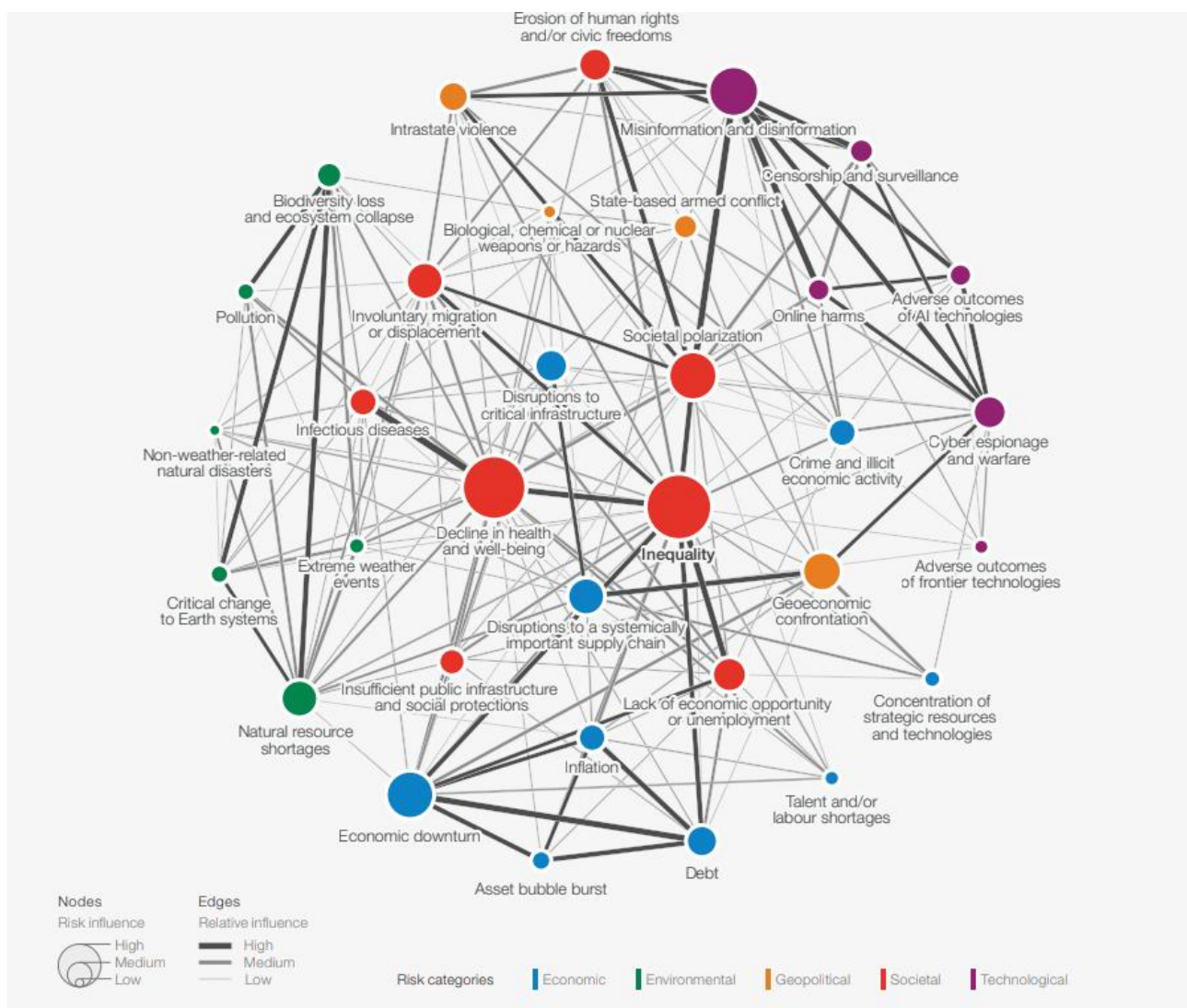


Global risk: “the possibility of the occurrence of an event or condition that, if it occurs, would negatively impact a significant proportion of global GDP, population or natural resources” (World Economic Forum, 2025)

The report uses the Global Risks Perception Survey (GRPS) as its primary data source, gathering insights from over 900 experts across sectors. Of the 33 identified global risks, these are categorised into five system domains: economic, environmental, geopolitical, societal, and technological.

Decoupling risk from systems involves identifying where dependencies lie, and how failure propagates. Systemic risk is also considered within the report by respondents evaluating potential consequences and interdependencies between risks. The interconnections map below identifies where risks might compound or cascade based on this data and shows that societal fractures and inequality are perceived as the most central risk of all, reinforcing the findings set out in Section 2.3.3. Incorporating these insights into transport planning might mean not only focussing on the resilience of physical assets but also ensuring equitable access to transport systems.

Figure 6 Global risks landscape: An interconnections map. Source: World Economic Forum Global Risks Perception Survey 2024-2025



Key Findings

- The UK transport system faces an **increasingly complex risk landscape** characterised by the interplay between hazards (e.g. extreme weather, cyberattacks), exposure (assets, people in harm's way), and vulnerability (susceptibility of systems to damage). Transport appraisal in this context will demand integrated, systems-based forms of risk assessment.

- The Global Risks Perception Survey (GRPS) identifies 33 global risks across five domains: economic, environmental, geopolitical, societal, and technological.
- **Acute risks are sudden, high-impact events**, such as severe weather, cyber threats, major accidents and pandemics, that can cause wide-ranging disruption and immediate loss of mobility, safety, and economic activity. Case studies highlight the vulnerability of transport to rare technical failures (e.g. NATS air traffic control outage) and extreme weather disasters (Stonehaven derailment, Cumbria landslides).
- **Chronic risks are persistent, evolving stressors**, such as climate change, infrastructure ageing, demographic shifts, technology dependencies, and workforce rigidities, that erode system stability gradually and can amplify the frequency and severity of acute incidents. Real-world events include the UK lorry driver shortage, and Hammersmith Bridge closures.
- **Acute and chronic risks are deeply interconnected**: chronic stressors like ageing infrastructure or workforce shortages often increase vulnerability and diminish response capacity during acute shock events, while recurring acute disruptions expose systemic weaknesses and reshape longer-term trends.
- The **risk landscape is changing rapidly**, with climate-driven weather extremes, greater cyber and geopolitical threats, and rising digital dependence all increasing the materiality, complexity, and frequency of shocks. This may demand dynamic forms of risk appraisal in a transport context and more forward-looking, adaptive resilience strategies across the transport system.
- **Cascading and compounding risks are increasingly significant**, as disruptions in one sector (e.g. energy, communications, healthcare) can rapidly propagate into transport, causing chains of failure with wide social and economic fallout. For example, surface water flooding can trigger system-wide disruptions via interdependencies with power supply and digital networks.
- Effective resilience interventions often fall outside the traditional transport domain, **requiring cross-sector collaboration and coordinated investment in shared infrastructure** (e.g. flood defences, power upgrades, workforce planning).
- Transport resilience appraisal must therefore capture **both immediate impacts and longer-term, system-wide consequences**. Systems thinking approaches are required to address dynamic risks, cross-sector dependencies and cascading failure potential.
- Resilience appraisal should directly inform prioritisation of resilience interventions across DfT, given the scale and diversity of risks facing the UK transport system. Strengthening transport appraisal and planning frameworks **are likely to be underpinned by interdisciplinary working, more continual risk monitoring, and broader subject matter expertise**. Decision-makers need to focus on **holistic system resilience**, recognising transport as both an enabler and a potential point of vulnerability within wider critical infrastructure.

3 Existing Transport Resilience Appraisal Frameworks

3.1 Appraising Resilience Across Transport Modes

When assessing whether an intervention offers Value for Money (VfM), an economic appraisal is used to assess all measurable costs and benefits that impact social welfare. The anticipated benefits from the intervention are identified in the strategic assessment, while the economic assessment appraises, and where possible quantifies, all relevant economic costs and benefits.

TAG-based appraisals seek to capture the full range of economic costs and benefits of transport schemes. These include the costs to deliver the intervention and manage any ongoing risks, the direct impacts on the users of the transport system and externalities that impact wider society.

This section explores the appraisal approaches that have been undertaken across different transport modes. The types of interventions where resilience is a primary objective or material benefit are set out, including understanding the role for resilience standards. Available information on existing appraisal approaches is summarised and exemplified through case studies. Given the general paucity of economic appraisal examples in publicly available literature, other forms of operational and performance assessment of resilience are also cited, where relevant. This section explores the four main transport modes: aviation, maritime, rail and road.

Key research question:

How is resilience currently being appraised across transport modes (including in resilience interventions and setting resilience standards)?

3.1.1 Aviation

Example Types of Resilience Interventions

The UK has the largest aviation network in Europe and the third biggest in the world contributing at least £22billion to the economy and supporting around half a million jobs (DfT, 2018). Aviation in the UK plays a crucial role in connecting people and goods to global destinations (ACOG and PA Consulting, 2023), making it a cornerstone of national transport resilience with an estimated value of more than £28 billion (ONS, 2020). Regional airports are also vital to connect distant parts of the UK where no effective rail routes exist (UK Parliament, 2020).

However, the sector faces a range of chronic and acute risks, including extreme weather, flooding, cyber threats, air traffic control outages, and disruption due to volcanic activity. Over the course of the pandemic, UK airports suffered a total revenue loss of £10bn (Airport Operators Association, 2022).

To mitigate these risks, airports have invested in infrastructure upgrades such as elevated runways, reinforced terminals, and improved drainage systems. International examples best illustrate the potential scale of these interventions, for example, Kansai International Airport in Japan elevated critical infrastructure following typhoon damage (Grey, 2025), while Don Mueang Airport in Bangkok installed berms and flood walls after severe flooding (ICAO, 2025).

Strategic infrastructure interventions also play a role in long-term resilience. Large-scale airport expansion projects, such as those proposed at Gatwick and Heathrow, aim to increase runway capacity and reduce bottlenecks, enhancing the UK's international connectivity and economic resilience through more diverse supply chains and more adaptive trade flows (DfT, 2025f).³ Similarly, modernising UK airspace could also strengthen its resilience, enabling authorities to better plan for, mitigate and address aviation-related incidents if they occur (ACOG and PA Consulting, 2023). An important lesson from the Covid-19 pandemic was the need for airports to diversify their operations to generate revenue beyond passenger traffic, for example through leveraging their real estate for commercial developments reinforcing their financial sustainability (Hirsh, 2021).

³ It should be noted, however, that concentrating operations at major hubs can introduce the risk of larger-scale disruption if these airports experience significant incidents, highlighting the need for robust contingency planning and diversification strategies to mitigate vulnerability.

Beyond physical assets, resilience in aviation includes organisational agility within airport business communities. A study commissioned by Resilience First and conducted by Thornton Tomasetti examined UK airports and their partners to identify best practice in agility. Key recommendations included linking resilience objectives to business outcomes, embedding resilience in new developments, and using horizon scanning and scenario planning to anticipate emerging technologies like automated vehicles and electric aircraft (Resilience First, 2019).

In the UK, airports are increasingly embedding climate adaptation into their masterplans and environmental management systems, aligning with national strategies such as Jet Zero (DfT, 2022a) and the Airspace Modernisation Strategy (CAA, 2023). The Civil Aviation Authority's *ARP4 Climate Change Adaptation Report* (2024) outlines how climate risk assessments are being integrated into airport planning, with a focus on interdependent and cascading risks. These strategies include measures to manage temperature extremes, precipitation changes, and sea-level rise, alongside broader sustainability commitments across the aviation sector.

Operational resilience is supported by structured contingency planning and emergency protocols (CAA, 2014). UK airports maintain detailed response frameworks, including coordination with emergency services, rerouting procedures, and rapid recovery strategies, as seen in Heathrow Airport's Operational Resilience Plan (CAA, 2014). Terminal systems are increasingly designed with built-in redundancies, such as backup power, heating, and cooling, to ensure continuity during outages (Secure Power, 2025). These measures are complemented by real-time analytics and predictive modelling, which help anticipate operational risks and enable proactive decision-making across the network (Guo et al., 2020).

Role of Standards in Delivering Resilience

Whilst there are no specifically defined and holistic 'resilience standards' for aviation, national and international regulations provide detailed requirements for infrastructure robustness, operational reliability, and emergency response. For example, the CAA's Licensing of Aerodromes (2022) set out baseline criteria for runway and taxiway asset quality, drainage capacity, and emergency provision.

Operational standards are reinforced by sector-wide frameworks, including from bodies such as the International Civil Aviation Organization (ICAO) and European Union Aviation Safety Agency (EASA). These frameworks cover contingency planning, incident management, and system redundancy. Industry-specific standards exist for asset maintenance, airfield safety, security, and operational risk assessment.

The Civil Aviation Authority's report on operational resilience at Heathrow and Gatwick outlines a framework for resilience planning, including risk management, contingency deployment, and joint business continuity planning (Steer Davies Gleave, 2014). It emphasises that airports should have robust resilience and continuity frameworks in place to manage disruption effectively. These frameworks typically focus on the response and recovery phase of the resilience cycle and lack a more strategic approach to resilience.

Recent evidence reinforces this gap. The Kelly Review (2025), commissioned after the 2025 Hyde Substation fire at Heathrow, concluded that resilience standards should extend beyond immediate operational continuity and embed systemic, forward-looking measures into regulatory frameworks. These should better reflect critical safety systems, support integration with energy suppliers, and involve development of a utilities masterplan.

Typical Approaches for Appraising Resilience Impacts

These standards effectively underpin the appraisal process in aviation by defining minimum acceptable levels of operational performance and risk mitigation (e.g. feeding into the definition of the 'Business As Usual' option).

Cost benefit analyses of specific adaptation measures have been undertaken. For example, Pagliara and Zingone (2023) appraise a resilience improvement at the Milan Malpensa airport against natural hazards by implementing infrastructure upgrade and a smart monitoring system in a multi-risk framework thereafter. Avoided losses were calculated in Do Nothing and Do Something scenarios. Impacts measured included reduced service interruption (hours/days), fewer diverted/cancelled flights, and lower associated passenger/cargo disruption impacts. Financial avoided losses included hourly airport revenue and socio-economic avoided losses included travel time savings (255,732 hours/year), reduced road/air distances, and reduced negative externalities (air pollution, climate, noise, accidents). These impacts were monetised using marginal cost values and time valuations. Probabilities were derived from historical event analysis and return period calculations (e.g. for floods, the baseline

assumed two floods every 10 years based on recent events and drainage inefficiency). These probabilities were applied to estimate avoided losses over a 22-year horizon. The overall benefit-cost ratio was 5.5, demonstrating significant VFM.

Beyond this, the appraisal of resilience impacts has been seen in larger schemes. For example, the Airports Commission Appraisal Framework (2014) for assessing alternative options for promoting airport capacity assessed resilience as part of the **operational risk assessment**. This assessment included the consideration of several disruptive events, including flooding, power outages, reduced fuel supplies, terrorism attacks, extreme weather events (including volcanic ash), and adaptability to climate change.

The assessment involved qualitative analysis supported by expert judgement and evidence from datasets such as flood risk maps, UK climate projections, and the National Risk Register. Importantly, the framework applied scenario analysis to explore how different risk profiles and mitigation strategies would affect operational continuity under varying future conditions. This allowed the Commission to test scheme resilience against multiple plausible futures rather than a single baseline.

The appraisal also evaluated residual risks after proposed mitigations, assessed the interaction of multiple simultaneous events, and examined the adaptability of designs to evolving threats. Outputs included risk rankings by likelihood and impact, identification of critical vulnerabilities, and recommendations for design features and contingency measures to enhance resilience at both the airport and system level. These findings **directly informed the Strategic and Management Cases**, ensuring resilience considerations were embedded in decision making. Whilst these operational risk factors did not feature in the Economic Case, some aspects of resilience relating to operational efficiency were weighed in the Economic Case. For example, this included the scheme's resilience in the face of severe weather and surface access transport disruption and its operational provisions to mitigate these impacts.

Scenarios have also been used in an operational planning context (see [Case Study 10](#), below), and these are supplemented by simulation exercises which are routinely conducted at airports to test emergency response capability, and their outcomes inform operational processes. These simulations help to identify single points of failure and evaluate alternative design or management options.

Case Study 10

UK airports: Improving operational resilience in response to disruption

The UK's major airports, especially Heathrow and Gatwick, have faced significant resilience challenges in recent years due to rising passenger demand, airspace congestion, and episodes of severe disruption. In the South-East, repeated capacity pressures and events like extreme weather (Image 10), technical failures, power outages and residual volcanic ash from nearby eruptions have exposed vulnerabilities in both airport and air traffic systems. Notably, Heathrow and Gatwick have regularly recorded some of the worst on-time performance in Europe.

In response to these issues, the Civil Aviation Authority (CAA) initiated a comprehensive review of airport operational resilience, consulting widely with airports, airlines, air traffic service providers, and industry groups. The findings, summarised in the CAP1515 report, highlighted the importance of efficient day-to-day management, proactive incident response, and clear communication with passengers during disruption. It was identified that collective action across the industry is needed, as resilience improvements can often benefit competitors and passengers across the system, not just the operator making the investment.

One outcome of the CAA's work was the formation of the Voluntary Industry Resilience Group (VIRG), a collaboration among major airports and airlines in the South-East. This group worked to develop system-level recommendations, including measures such as improved use of standby systems, contingency planning for power and airspace outage, and regular delay causation analysis.

Regulatory frameworks and licence conditions were also reviewed, with CAA guidance encouraging airports to build resilience into infrastructure upgrades and daily operations. For example, investments in backup generators, rapid runway repair capability, and enhanced ground handling procedures were justified based on reduced vulnerability to both planned and unplanned closures. To guide decision-making, VIRG employed delay causation analysis, schedule realism assessments, and scenario modelling to identify systemic vulnerabilities. Recommendations were

prioritised based on cross-network benefits and feasibility, with effectiveness tracked through operational performance metrics (such as on-time departure rates, cancellation frequency, and passenger delay minutes) and stakeholder feedback (through mechanisms such as post-disruption reviews, collaborative workshops, and periodic reporting to the Civil Aviation Authority).

Image 10 Many UK airports face moderate to high flood risk, with climate change expected to increase both frequency and severity of such events.



3.1.2 Maritime

Example Types of Resilience Interventions

The maritime sector, and ports in particular, are exposed to a wide range of shocks that can disrupt operations and impact global trade. Key risks include extreme weather events such as storms, flooding, and high winds, as well as climate change impacts like sea level rise and prolonged droughts, which have already constrained major shipping routes such as the Panama Canal. In addition, operational disruptions including machinery failures, collisions, and fires, remain persistent, while cybersecurity threats have escalated, with over 1,800 vessels targeted by ransomware and malware attacks in the first half of 2024 alone. These events can lead to temporary port closures, rerouting of vessels, and severe congestion, resulting in significant economic losses and cascading effects across global supply chains (Inmarsat, 2025).

To address these risks, maritime resilience interventions cover infrastructure, operational, and strategic areas. Infrastructure interventions may include physical upgrades to port facilities such as constructing or raising flood defences, breakwaters, and quay walls and deploying improved drainage and pumping systems to manage heavy rainfall. Engineering solutions increasingly include climate adaptation, such as elevating critical assets and reinforcing assets against future sea level rise (UNCTAD, 2022).

Large-scale strategic maritime investments, such as the planned upgrades to the Thames Barrier under the Thames Estuary 2100 Plan, are expected to deliver significant resilience benefits by **protecting 1.42 million people and £321 billion of assets from tidal flooding**, while incorporating adaptive, low-carbon measures and natural capital enhancements (JBA Consulting, 2024).

Operational resilience in ports and the wider maritime sector relies on **comprehensive contingency planning and proactive risk management**. This includes real-time monitoring of weather, tides, and vessel traffic, as well as **scenario planning** to anticipate disruptions (UNCTAD, 2022). Emergency preparedness measures encompass regular drills, clear protocols for rapid shutdown and restart, and structured coordination with first responders and local agencies. Maintenance strategies prioritise rapid inspection and repair to restore operations quickly after incidents. In parallel, ports are strengthening

cyber resilience through risk assessments, network segmentation, redundancy, and continuity planning for IT and communications systems to safeguard critical operations (IAPH, 2021).

Role of Standards in Delivering Resilience

International standards play a key role in strengthening maritime resilience. Organisations such as the International Maritime Organization (IMO) and the International Association of Ports and Harbors (IAPH) provide guidance on risk management, port safety, and climate adaptation. The Resilience4Ports framework brings together best practice tools and benchmarking to support ports in identifying risks, conducting scenario analysis, and embedding resilience into strategic planning (Davey et al., 2021).

In the UK, the Port Marine Safety Code (PMSA) and its accompanying Guide to Good Practice require ports to undertake formal risk assessments and maintain Port Emergency Plans, which must be regularly tested and updated (Department for Transport and Maritime and Coastguard Agency, 2025). These documents also provide practical guidance on safe design and maintenance of marine infrastructure, supporting structural robustness and operational continuity. Additionally, ports are required to disclose their resilience and climate adaptation measures under the Climate Change Act 2008 Adaptation Reporting Power, which mandates reporting to Defra on actions taken to address climate risks (Defra, 2025a).

Typical Approaches for Appraising Resilience

Typical approaches for appraising resilience include **cost-benefit analysis** (see Section 3.3), which has been applied for appraising adaptation measures for major infrastructure projects including assessing avoided losses such as reduced asset damage and service downtime. These frameworks generally estimate these benefits over the asset lifecycle using probabilistic modelling and discounting future values. Reduced asset damage is assessed by applying global risk estimates and models to quantify avoided repair costs and service outages (Hallegatte et al., 2019).

For example, internationally, ports such as Rotterdam have used cost-benefit analysis to prioritise adaptation measures, examining whether resilience investments deliver net economic benefits ([Case Study 11](#)).

Examples of appraisals of major infrastructure investments which have valued resilience have been more challenging to locate. One maritime example is the **Thames Estuary 2100** project which during its most recent Economic Case Review applied a more standardised Net Present Social Value analysis with **an adaptive pathways approach** as part of a comprehensive reassessment of costs and benefits over the remaining 90-year life of the plan. This incorporated the latest UKCP climate projections to model design flexibility under various sea-level rise scenarios by 2100. This adaptive design allows incremental upgrades to flood defences, including the Thames Barrier, rather than a single large intervention, enabling the costs and benefits under uncertainty to be appraised. This appraisal considered both direct losses, such as damage to homes, businesses, and transport infrastructure, and indirect impacts, including disruption to London's economy, emergency response costs, and cascading effects on utilities and transport networks (Environment Agency, 2023; JBA Consulting, 2024).

In an operational context, ports deploy **simulation tools, scenario planning, and stress testing** to model the impacts of extreme events, assess operational continuity, and identify single points of failure in shipping and cargo handling (HogoNext, 2024).

Case Study 11

Rotterdam Port Adaptation Strategy – ongoing since 2017

The implementation of the Rotterdam Port adaptation strategy is a global example of resilience planning in the maritime sector in response to climate change and growing flood risks. Rotterdam, Europe's largest port (Image 11), is critically important to both the Dutch and wider European economy, handling over 460 million tons of cargo annually. Its location outside the Netherlands' dike system exposes it to heightened risks from sea level rise, storm surges, and extreme rainfall.

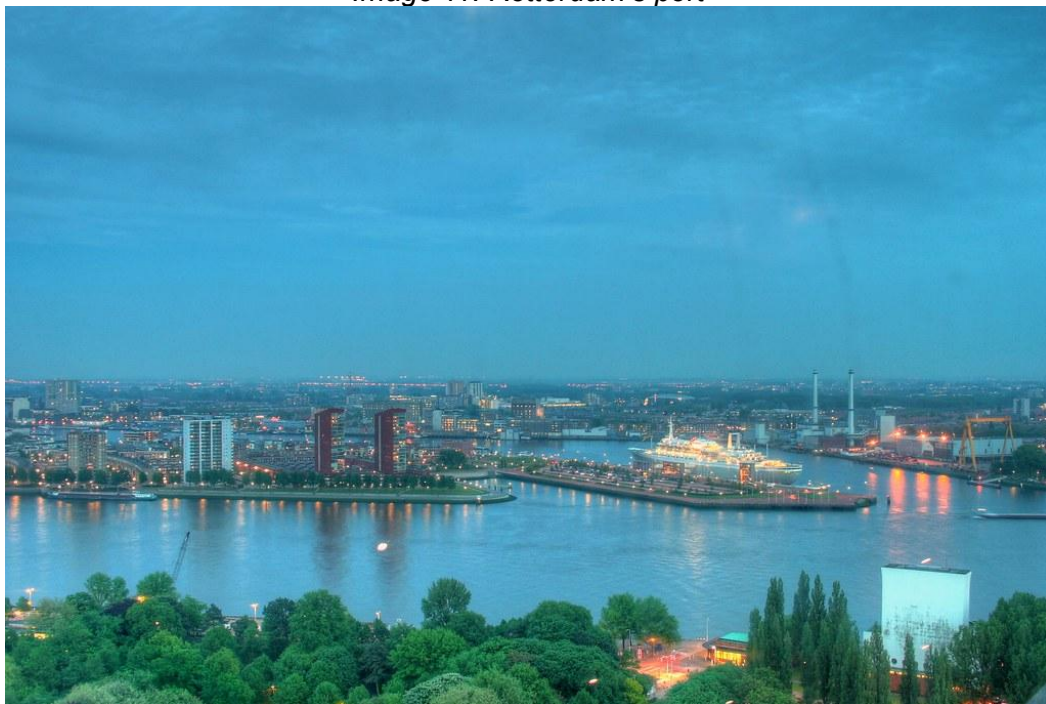
Recognising these vulnerabilities, the Port Authority launched an adaptation strategy in collaboration with the municipality, government agencies, and private stakeholders. The strategy combines prevention, spatial adaptation, and crisis management measures, underpinned by rigorous scientific modelling, stakeholder engagement, and a detailed cost-benefit analysis to prioritise interventions. Measures include raising embankments and quay walls, compartmentalising high-value areas to limit flood spread, reinforcing drainage systems, and developing facility-specific

emergency plans. Regular stress tests and scenario planning ensure that measures remain aligned with evolving climate projections and port development plans.

The cost-benefit analysis assessed both direct and indirect benefits over a multi-decade horizon, estimating that an investment of €90 million would deliver approximately €611 million in avoided future damages, equating to a Benefit-Cost Ratio of 6.8. This figure represents the present value of avoided losses calculated using probabilistic risk modelling based off national standards and methodologies for flood risk management, as set out in the *Dutch Delta Programme*. Climate projections from KNMI and Hydra-NL informed scenarios for sea-level rise and storm surge probabilities, which were combined with hydraulic models to estimate flood depths and extents for different time periods. Expected annual damages were derived by multiplying the probability of each flood scenario by its estimated economic loss, then discounted. Direct impacts included repair and replacement costs for quay walls, embankments, drainage systems, warehouses, and utilities, while indirect impacts covered business interruption for logistics and manufacturing tenants and cascading effects on European freight corridors.

This evidence provided a clear economic case for prioritising cost-effective measures and informed decision-making across different port areas. Alternative options, such as a large-scale lockable barrier similar to the Maeslant Barrier, were evaluated but rejected due to significantly higher costs (€820 million) and a lower BCR, despite higher absolute benefits.

Image 11. Rotterdam's port



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Source: <https://climate-adapt.eea.europa.eu/en/metadata/case-studies/rotterdam-port-adaptation-strategy-for-climate-resilient-transport-and-business-activities>

3.1.3 Rail

Example Types of Resilience Interventions

Extreme weather and climate change is one of the biggest challenges facing the railway today (Network Rail, 2024). In the Netherlands, 4-10% of rail failures are linked to adverse weather conditions, with 1,230 disruptions in 2018 alone due to extreme weather. In the UK, buckling railway tracks are expected to become four to five times more frequent by the 2050s (Climate Adaptation Platform, 2025).

To combat this, Network Rail's Weather Resilience and Climate Change Adaptation (WRCCA) Plans outline physical upgrades such as enhanced drainage systems to prevent flooding, reinforcement of earthworks to reduce landslip risks, and the use of heat-resistant materials to mitigate track buckling during heatwaves. These measures are particularly important considering incidents like the Stonehaven derailment, which highlighted vulnerabilities in earthwork stability during extreme weather.

In 2021, the Emergency Management Review (Rail Delivery Group) set out recommendations for strengthening resilience across the rail industry. These recommendations have since been implemented through the Rail Resilience Project (Rail Delivery Group and PA Consulting, 2025a), establishing a comprehensive framework that includes a suite of resilience standards covering governance, risk assessment guidance, and a resilience measurement framework, alongside an Integrated Emergency Management competency model and self-assessment tools for organisational capability. Operationalised through RDG guidance, these measures standardise protocols for incident response, improve coordination with emergency services, and build institutional capacity to manage disruptions.

Finally, strategic planning plays a key role in embedding resilience into long-term investment decisions. Network Rail's regional WRCCA plans tailor interventions to local climate risks, while resilience is increasingly integrated into Control Period 7 (2024–2029) planning, a five-year planning and funding cycle for Network Rail.

Role of Standards in Delivering Resilience

Whilst demonstrating the sector's growing commitment to resilience, the effectiveness and consistency of these interventions depend on the standards and frameworks guiding their design and implementation. For example, rail sector stakeholders including the Rail Safety and Standards Board (RSSB) has developed a Rail Resilience Strategy (2025), a five-year roadmap running to 2030. This strategy focuses on four strategic themes: risk, collaboration, governance, and leadership. Key initiatives include:

- The creation of a Rail Operational Risk & Resilience Index (RORRI) to track and anticipate risks
- Horizon scanning to identify emerging threats
- A strategic playbook to embed resilience practices across the industry

The Rail Delivery Group have also produced holistic industry leading guidance on resilience. The RDG Resilience Guidance (Rail Delivery Group and PA Consulting, 2025a), outlines a comprehensive competency framework and provides self-assessment tools designed to embed Integrated Emergency Management (IEM) capabilities within rail entities. Here, resilience is not assessed as a standalone benefit but as a minimum baseline for system performance. KRIs (key risk indicators) and KPIs (key performance indicators) are used to understand several principles of resilience. Indicators within the example of awareness principle are as follows:

- **KRI:** Identify when more than 10% of IEM discussions, approvals or decisions request further information
- **KPI:** Review decision making processes, timescales, information supplied and results

Further information is provided in [Case Study 1](#) within section 2.1.5.

Typical Approaches for Appraising Resilience

A range of measures for appraising resilience have been seen in the rail resilience literature which are explained in more detail below.

Table 9. Summary of the different Approaches for Appraising Resilience for Rail

Approach	Description	Example Output	Example Source
Scenario Analysis	Tests performance under multiple plausible futures (e.g., flooding, heatwaves)	Recovery cost, Disruption duration	Poo et al. (2024)
RORRI	Strategic risk prioritisation for investment planning	Ranked risk scores, investment prioritisation focus	RSSB (2025)
Cost-Benefit Analysis	Compares costs and benefits for multiple interventions	Benefit Cost Ratios	DfT Winter Resilience (2011)

Multi-Criteria Assessment	Weighs resilience with other objectives (safety, environment, cost)	Composite MCA score	Dawlish Case Study (Case Study 12)
Maturity Assessment	Evaluates organisational resilience capability	KPI/KRI dashboards	Rail Delivery Group (2025)

Under the Department for Transport’s *TAG Unit A5.3: Rail Appraisal* (2025g) framework, **scenario analysis**, as part of risk and uncertainty toolkit, is advised to assess performance under different future conditions, which can be configured to pick up downside shocks. This aligns with the Common Analytical Scenarios (CAS) introduced in the TAG Uncertainty Toolkit (DfT, 2025j), which provide a consistent set of seven plausible futures covering uncertainties in the economy, technology, behaviour, and decarbonisation.

Scenarios are increasingly applied in rail resilience research to evaluate system performance under extreme conditions such as flooding and heatwaves. This approach is particularly relevant for rail, where long asset lifecycles and high capital costs make forward-looking appraisal critical (DfT, 2024c; NIC, 2022). For example, Poo et al. (2024) used **scenario analysis** to simulate rail network performance under three climate scenarios (2025, 2030, 2050), and assess parameters such as resilience capacity, disruption duration, and recovery cost. Their analysis quantified risk levels for hazards including flooding, heatwaves, and sea-level rise. This approach helps planners understand vulnerabilities and stress-test robustness and recovery capacity.

The Rail Operational Risk & Resilience Index (RORRI), developed by the Rail Safety and Standards Board (RSSB, 2025), represents a more strategic approach to resilience assessment. It **tracks and prioritises risks across the network, supporting the strategic context and case for change** for an intervention to improve resilience. For instance, RORRI has been used to inform asset management investment priorities in Control Period 7 (2024–2029), helping Network Rail allocate resources to high-risk areas based on forecasted climate and operational threats.

Cost-benefit analysis has been used to compare the relative costs of multiple different resilience interventions against the benefits. For example, the Department for Transport’s Winter Resilience in Transport (2011) study compared the costs of measures such as third rail heating, de-icing equipment, and salt storage against performance metrics like avoided train delays and reduced salt wastage, under different weather scenarios. Benefits were monetised using various metrics, including standard values for average savings per minute (e.g., £41.60 per minute), and outputs were expressed as Benefit-Cost Ratios (BCRs) for each intervention. This approach enabled decision-makers to identify the most Value for Money resilience options despite uncertainty about future conditions.

Multi-criteria assessment frameworks have also included resilience criteria in some rail project appraisals (see [Case Study 12](#), below).

Case Study 12

Dawlish Rail Line Collapse – February 2014

The collapse of the sea wall at Dawlish in February 2014 (Image 12) remains one of the most significant events affecting UK transport resilience. Severe storms breached the sea wall protecting the Great Western Main Line, causing around 80 metres of track to collapse - leaving rails suspended above the exposed ground. The incident closed the primary rail link between Exeter, Plymouth, and Cornwall for eight weeks, isolating large parts of the South West and causing widespread disruption. The cost of reinstating the line was approximately £50 million, while the wider economic impact was estimated at over £1 billion.

In the aftermath, Network Rail commissioned the Exeter to Newton Abbot Geo-Environmental Resilience Study (2016) to develop a long-term strategy for safeguarding this critical route. The study adopted a **multi-criteria assessment framework** that evaluated options against technical feasibility, safety, environmental impact, and whole-life cost. This approach also recognised wider resilience benefits, including the potential for reduced maintenance expenditure, avoidance of emergency repairs, job creation during construction, and improvements to public amenity along the coastal corridor.

A TAG-based economic appraisal compared the “Do-Minimum” baseline with the proposed Resilience Strategy, which delivered a Benefit-Cost Ratio of around 2.0, potentially indicating “High” Value for Money. Sensitivity testing confirmed that the strategy would continue to deliver VfM over a 100-year horizon, reflecting the long design life of the proposed interventions. These figures exclude unquantified benefits such as tourism resilience and regional economic stability.

Image 12. Extensive repair work of the Dawlish rail line had to be undertaken following an intense storm on 4-5 February 2014.



This photo by [Lewis Clarke](#) is licensed under [CC BY-SA 2.0](#)

Source: [Exeter to Newton Abbot Geo-Environment Resilience Study - Executive Summary](#)

3.1.4 Road

Example Types of Resilience Interventions

Roads remain the most essential form of connection between communities (Arup, 2025), highlighting their centrality to transport system resilience. Resilience interventions in the road sector can be broadly categorised into infrastructure, operational, and co-benefitting in nature.

Infrastructure interventions include physical upgrades to assets, such as drainage systems, road surfaces, and structural components. For instance, in late 2024, National Highways completed a £1.3 million drainage improvement scheme at Notter Bridge in South-east Cornwall to address recurring rain-related crashes and flooding. This involved upgrading drainage, clearing vegetation, and renewing barriers to mitigate future flooding and improve safety. Similarly, National Highways is extending the life of its concrete roads through a long-term repair and replacement programme using modern, more resilient materials (National Highways, 2020), and updating standards to better address freeze-thaw cycles.

Operational interventions focus on system management and response. Real-time traffic management systems are deployed on parts of the Primary Route Network to reroute vehicles during incidents, while integrated weather forecasting enables pre-emptive deployment of maintenance crews. The Essex Highways Resilient Network Strategy exemplifies this approach, setting performance targets for different road hierarchies and prioritising maintenance on key routes to ensure access during adverse conditions.

Co-benefitting interventions deliver resilience alongside wider environmental or social benefits. Nature-based solutions, such as bioswales, permeable surfaces, and green verges, are increasingly used to manage water, reduce heat, and enhance biodiversity. Arup's Road to Resilience (2025) guide highlights how Sustainable Drainage Systems (SuDS) contribute not only to flood mitigation but also to environmental quality and community wellbeing. While SuDS have been subject to cost-benefit analysis in retrofit and urban drainage contexts, their integration into transport appraisal frameworks is limited.

Role of Standards in Delivering Resilience

The Design Manual for Roads and Bridges (DMRB) sets out the technical standards for the design, assessment, and operation of trunk roads and motorways in the UK. Within this framework, *LA 114 – Climate* provides specific guidance on assessing and reporting the effects of climate on highways, including both climate change resilience and adaptation. It outlines requirements for evaluating the vulnerability of transport assets to future climate scenarios and integrating mitigation strategies into design and maintenance planning. This includes scoping studies, baseline assessments, and the use of significance criteria to determine climate-related risks to infrastructure performance.

While DMRB standards already incorporate some resilience considerations, the Chartered Institution of Highways and Transportation (CIHT) recommend taking this further within their detailed guidance for the highways and road transport sector. The Delivering a Resilient Transport Network report (introduced in Section 2.2.1) stresses the importance of updating design standards to reflect future climate scenarios, warning that infrastructure built to outdated specifications may require costly retrofits within decades.

Typical Approaches for Appraising Resilience

Performance assessment of the resilience of highways structures at the asset-level is undertaken by highways authorities in line with the DMRB, progressing through three stages: identifying constraints and options (Stage 1), assessing alternatives (Stage 2), and detailed evaluation of the preferred scheme (Stage 3). An example of performance assessment at the asset level is also Atkins (2007) *Guidance Document for Performance Measurement of Highway Structures*. This uses a 'Reliability Performance Indicator' to quantify the ability of a structure of support traffic considering the consequence of failure to road users, businesses, and communities.

Highways authorities such as National Highways undertakes **programme and portfolio level analysis** to support decision-making on maintenance expenditure, supporting overall resilience of the network (see [Case Study 16](#)). Exploratory resilience appraisal following the National Highways Appraisal Manual has been undertaken on major enhancement projects which are expected to have material resilience impacts, such as Lower Thames Crossing (LTC) (see [Case Study 17](#)).

Brunson and Norman (2024) authors propose a qualitative, holistic resilience assessment framework for appraising road resilience based on case studies which included the A487, A120 and A2 Dover Access.

International examples such as the ICARUS climate adaptation programme for European roads have also followed a cost benefit analysis approach for appraising the benefits of improved resilience (CEDR, 2022). Losses were measured in the Do Nothing and after implementing adaptation measures. These included direct costs (asset repair), indirect costs (travel time, economic disruption) and intangible benefits. Quantification used a hazard assessment and was expressed as reductions in Expected Annual Damages (EAD). Co-benefits were monetised using methods like contingent valuation and benefit transfer. Sensitivity analysis and scenario modelling were used to address uncertainty in the core results.

Key Findings

- Resilience appraisal practices **vary significantly across transport modes**, reflecting their distinct risk profiles, operational contexts, and standards frameworks.
- **Aviation resilience appraisal** commonly applies qualitative risk assessments, scenario analysis, and expert judgement, with resilience typically treated as baseline risk mitigation within strategic and management cases rather than fully monetised benefits.

- **Maritime resilience** appraisal methods include project-level cost-benefit analysis, scenario planning, and stress testing, which quantify both direct and indirect resilience benefits, such as avoided downtime and supply chain continuity.
- **Rail resilience** appraisal is potentially the most mature, supported by RDG's comprehensive guidance, which embeds a competency framework, self-assessment tools, and a resilience measurement approach alongside governance and risk guidance. These standards complement strategic risk indexing (e.g., RORRI), multi-criteria assessment, scenario modelling, and cost-effectiveness analysis, enabling a structured and consistent basis for appraising resilience capability.
- Road resilience appraisal takes **asset-level and programme-level approaches**, using scenario analysis, reliability indices, and stress testing to quantify performance improvements and inform investment prioritisation.
- Across all modes, **regulatory and industry standards play a critical role in setting minimum resilience baselines**, but the absence of fully consistent or holistic resilience standards risks leading to fragmented appraisal approaches and potential gaps in resilience integration and the impact of system interdependencies.
- **Scenario analysis, simulation exercises, and stress testing** are widely used to assess resilience performance; however, many resilience benefits remain difficult to monetise, limiting their visibility in cost-benefit analysis and VfM assessments.
- Leading case studies (e.g., Heathrow/Gatwick operational resilience, Thames Estuary 2100, Rotterdam port adaptation, Dawlish rail collapse) demonstrate the value of combining strategic planning, modelling, and collaborative industry action to deliver system-wide resilience outcomes.
- Despite progress, the literature highlights persistent gaps in the consistent integration of resilience into appraisal frameworks, particularly in monetisation and cross-sector standards, underscoring the need for forward-looking, evidence-based guidance to ensure that the full range of resilience benefits is captured and supported.

3.2 Forms and Dimensions of Transport Resilience Appraisal

In this context, forms refer to the different types of resilience considered in transport systems (for example, economic, network, or workforce resilience), while dimensions describe the aspects or scales at which resilience is assessed (such as local and regional levels). This section builds on the mode-specific research in Section 3.1 and examines how these forms and dimensions have been appraised in the literature. It includes economic resilience, route and network resilience, local and regional resilience, and workforce resilience. We seek to address the following research question:

Key research question:

What forms of resilience have been appraised (e.g. route and network resilience), what are the common dimensions and how do they differ?

3.2.1 Economic Resilience

Economic resilience is “the ability of the economy and economic actors, particularly individuals, organisations and institutions, to prepare for and adapt to changing conditions and withstand and absorb shocks”.

Capturing Economic Resilience in HMT Green Book Value for Money Assessments (2025)

Table 10 Three Dividends of Economic Resilience Framework. Source: Triple Dividend framework based on Rodin (2014), WRI (2019), Heubaum et. al. (2022) and Field et. al. (2024)

Dividend	Description
----------	-------------

Dividend 1: Avoided Losses	The reduction or avoidance of losses to individuals, businesses, the economy and society by reducing the likelihood of an underlying threat/risk occurring or reducing the impact if the threat/risk were to occur.
Dividend 2: Economic Benefits	The economic benefits generated during non-emergency times, including direct economic impacts and impacts felt through the supply chain and wider economy.
Dividend 3: Social and Environmental Benefits	The social and environmental benefits generated during non-emergency times, including impacts on local communities, health/wellbeing and carbon emissions.

This highlights how improved resilience might not only reduce losses when threats materialise but also deliver economic, social, and environmental gains in stable periods. For example, an investment in an Early Warning System could reduce economic damage during a shock (Dividend 1), improve investor confidence and lower financing costs in non-emergency times (Dividend 2), and support the protection of natural capital like mangrove forests (Dividend 3).

Using this appraisal framework as a foundation, this guidance aimed to codify new methodologies for analysts and decision-makers to better appraise these impacts in a proportional way. **Strategic, economic and risk and uncertainty assessment tools** were identified, offering different routes for analysis depending on the level of complexity and significance of the spending that different resilient interventions involve. Relevant methods are explored in more detail in the remainder of Section 3.

This Three Dividend approach is consistent with the ‘Triple Dividend’ framework set out in Defra’s Climate Adaptation Supplementary Green Book guidance (2025b). This framework similarly recognises not only the first dividend of avoided losses when risks materialise, but also the second and third dividends: co-benefits to the economy, society, and environment that accrue even if disruptive events do not occur. This highlights how resilience investments can contribute to broader economic activity, improve health and wellbeing, and deliver environmental gains irrespective of shocks occurring.

3.2.2 Route and Network Resilience

As described in Section 2.1.3, a key distinction which emerges in transport resilience literature is route resilience, focused on individual corridors or assets, and network resilience, considering the overall performance of a transport system. The National Highways Appraisal Manual is the most comprehensive study outlining an economic appraisal of route and network resilience and this is discussed in more detail in Section 3.3.1. Other operational and performance related assessments of route and network resilience are described below.

Route Resilience

Route resilience refers to the capacity of a **specific corridor, link, or section of a transport system**, such as a major road or railway segment, to withstand disruptive events and quickly restore functionality following such incidents, particularly in locations where alternative routes are few or do not exist.

The *Guide to Road Safety Route Treatments, National Highways (2025b)* cites the **International Road Assessment Programme (iRAP) star rating system** as one method for assessing infrastructure safety and resilience is one of the components assessed. Roads are rated from 1-star (high risk) to 5-star (low risk). To complement the iRAP framework, the guide promotes the use of the Route Review Tool (RRT). This tool enhances the interpretation of iRAP data by allowing practitioners to assess Star Ratings estimates at multiple scales, including route, section, and 100-metre intervals, and model the impacts. An example assessment of route resilience using this approach was highlighted in National Highway’s ARP4 Report (2024a) (see [Case Study 13](#), below).

Case Study 13

Route resilience: Hull Tidal Defence Scheme

Hull has long been one of the UK’s most flood-vulnerable cities, with its low-lying geography and proximity to the Humber Estuary making it particularly susceptible to tidal surges. Notably, the 2013 North Sea tidal surge caused widespread disruption, flooding hundreds of properties and

threatening key transport links (Image 15). Events like this have underscored the need for robust flood defences to protect both communities and infrastructure.

Image 13. Tidal flood inundating Victoria Dock Village river front, Hull in 2013.



This Photo by [Ian S](#) is licensed under [CC BY-SA 2.0](#)

As highlighted in the ARP4 Report, the Hull Tidal Defence Scheme exemplifies a strategic, multi-agency approach to safeguarding transport infrastructure from climate-related risks. The scheme protects key arterial routes – the A63 and A1033 – from tidal inundation, which has historically posed significant threats to connectivity and safety in the region. Delivered in partnership with the Environment Agency, the project incorporated £3 million of targeted investment from National Highways. This contribution formed part of a broader resilience strategy aimed at fortifying critical infrastructure in flood-prone zones, ensuring continuity of movement and economic activity during adverse weather events. The following benefits can be inferred from the report:

Dividend	Example application
Avoided losses	<i>Provides a 1-in-200-year tidal flood protection (or ~14% chance in a 30 year period) – reducing the likelihood of closures, detours and economic disruption.</i>
Economic benefits	<i>Boosted investor confidence in Hull's regeneration zones, including the Victoria Pier and St Andrew's Quay Retail Park.</i>
Social/environmental benefits	<i>Avoided flood-related congestion and detours helps reduce transport-related CO₂ emissions.</i>

Network Resilience

Network resilience assesses the transport system's capacity to maintain operations and ensure **trips can be completed as a whole**, even when individual links or segments are disrupted. It highlights the importance of redundancy and connectivity, focusing on the existence, quality, and capability of alternative routes that allow transport users to reach their destinations when specific parts of the network are compromised. This may include **multi-modal solutions** (see [Case Study 14](#), below).

Here, assessment methods have addressed **system-wide stress scenarios and criticality assessments**. For example, The International Transport Forum (ITF) in its *Transport Network Resilience (2025)* policy paper outlines a suite of analytical tools aimed at helping policy makers assess vulnerabilities and anticipate cascading failures. These include **impact assessments to quantify disruption consequences, digital twins and modelling** to simulate failure scenarios, and horizon scanning to identify emerging risks. The paper also emphasises the importance of mapping interdependencies between transport and other critical systems, such as energy and communications, noting that localised disruptions can quickly escalate into systemic crises.

Case Study 14

Multi-modal interventions to improve network resilience following landslides and embankment failure along the A591 in Cumbria

The A591 was part of a turnpike (a 17th-19th century tollroad), which was subsequently expanded in the late 1800s utilising embankments backfilled with soil and peat from nearby reservoir works. During Storm Desmond, 405mm of rain fell in Thirlmere in 38 hours, setting a new national record for rainfall over two consecutive rain-days. The heavy rainfall saturated the backfill of retaining walls and resulted in a major embankment failure, along with debris landslides along the route (Image 17).

Image 17. Earthwork failures along the A591 in Cumbria during Storm Desmond, 2015.



These stills from [YouTube video](#) "THIRLMERE SIMON Q&A" by Cumbria County Council is licensed under [CC BY 2.0 DEED](#)

As the road repairs took some time to be completed, and diversionary routes were very long, Cumbria County Council provided some localised multi-modal alternatives. A temporary pedestrian, cycle and horse-riding path was built. A small forest road was upgraded to provide access for a shuttle bus service to transport children cut off from their primary school. This was later expanded to the wider population and by April had been used by 30,000 people. This forest road was wide enough for a small bus but not for general traffic, and a park-and-ride service was put in place for passengers using it to bypass the collapsed section. The next available diversionary route was an additional 20 miles in length via the steep Kirkstone Pass. Selected resilience dividends are listed in the table below:

Dividend	Example application
Avoided losses	Shuttle bus service on a forest road reconnected children to their primary school, avoiding absences from school
Economic benefits	Park-and-ride and shuttle services enabled continued access to shops, services, and employment, reducing economic losses from isolation
Social/environmental benefits	A pedestrian, cycle, and horse-riding route was constructed to promote low-carbon travel.

3.2.3 Regional Resilience

Transport resilience literature also delineates transport impacts between local and national systems (Royal Town Planning Institute, 2021). Local transport networks are often the first to experience the impacts of extreme weather events, such as flooding, heatwaves, and storms, which can disrupt daily mobility, isolate communities, and damage critical infrastructure. Recognising this, the DfT's *Transport Adaptation Strategy* (2025), calls on local authorities to embed resilience into every stage of transport planning and delivery.

Examples of local or regional-level assessment frameworks have been challenging to locate, but it is understood that Local Resilience Forums (LRFs) are currently exploring **quantitative indicator frameworks** in the design of their monitoring and evaluation approaches.

LRFs are multi-agency partnerships established under the Civil Contingencies Act (2004), bringing together emergency services, local authorities, transport operators, health bodies, and utility providers.

Their role is to plan for and respond to emergencies, including transport disruptions caused by severe weather or infrastructure failure. LRFs develop Community Risk Registers, conduct joint exercises, and ensure that transport resilience is integrated into broader emergency planning. They also facilitate communication between stakeholders during incidents, helping to coordinate road closures, diversion routes, and public information. Potential resilience dividends from LRFs are suggested below:

Table 11 How LRF impacts might be included in resilience appraisal. Source: PA Consulting analysis.

Dividend of Resilience	LRF Impacts	Example metric for appraisal use
Avoided loss	During Storm Arwen, LRFs in North East England coordinated rapid response to power outages and road closures, reducing disruption and preventing further harm.	Number of incidents with reduced response time.
Economic benefits	LRFs working with local businesses on continuity planning helped maintain operations during COVID-19 lockdowns and supply chain disruptions.	Insurance premium reductions due to risk mitigation.
Social/environmental benefits	In Cumbria, LRFs supported isolated communities during Storm Desmond, coordinating transport and welfare services.	Number of vulnerable individuals supported.

While Local Resilience Forums provide important coordination for emergency response, **city resilience frameworks** often offer a more structured and indicator-based approach to resilience assessment. Two notable examples are the City Resilience Index (CRI),⁴ developed by Arup and the Rockefeller Foundation, and the Buro Happold Resilience Insight Tool.⁵ Both frameworks emphasise holistic, cross-sectoral strategies and provide practical metrics that could complement transport appraisal, particularly for capturing local priorities and systemic interdependencies beyond emergency planning.

Operational and performance assessment of resilience at a local-level is more evident. For example, Early Warning Systems (EWS) such as the Hydro-Logic Smart Monitoring System, the Flood Forecasting Centre and the Landslide Early Warning System (see [Case Study 15](#), below) assess localised risks daily. Their National Academies' *Investing in Transportation Resilience: A Framework for Informed Choices* (2021) paper highlights that their value can be captured in appraisal through metrics such as reduced downtime, avoided damage, and improved safety outcomes.

Case Study 15

Landslides Early Warning System

The British Geological Survey (BGS) designed and manages a local Landslide Early Warning System (LEWS) for Scotland. A computational model which supports the LEWS is run twice daily and uses rainfall, temperature and relative humidity measurements and forecasts. The LEWS in Scotland does not issue automatic advisories, however BGS prepare heuristic daily landslide advisories, based on historic threshold levels which feeds into the Daily Hazard Assessment (DHA) for Great Britain.

While there are no publicly documented case studies yet showing a specific event in Scotland where the Landslide Early Warning System (LEWS) directly led to avoided losses, economic benefits, and social/environmental gains, potential dividends from this system can be inferred based on its operational design and parallels with similar systems globally:

⁴ The CRI provides a globally recognised framework built around four dimensions: Health and Wellbeing, Economy and Society, Infrastructure and Ecosystems, and Leadership and Strategy. These dimensions are supported by twelve goals and fifty-two indicators, covering areas such as safeguarding health, maintaining critical services, enabling inclusive governance, and reducing exposure to hazards. The index combines qualitative and quantitative assessment to diagnose strengths and weaknesses, track progress, and inform integrated urban planning (Arup and Rockefeller Foundation, 2014).

⁵Buro Happold's city resilience tool evaluates resilience through a demand and capacity model, comparing the risks posed by selected shocks and stresses against a city's mitigation measures and adaptive capacity. It uses a structured process to assess vulnerability across twelve components, including governance, infrastructure, resources, and social systems, and generates outputs such as resilience ratings and estimated financial impacts (Field, 2016).

Dividend	Example application
<i>Avoided losses</i>	<i>Potentially helps prevent injuries and vehicle damage through advisories during high-risk rainfall events</i>
<i>Economic benefits</i>	<i>Supports improved infrastructure planning and investment decisions by transport agencies and councils</i>
<i>Social/environmental benefits</i>	<i>Protects ecosystems from sediment runoff through prompting pre-emptive slope stabilisation action</i>

To ensure that local and regional priorities are reflected in investment decisions, authorities are encouraged to adopt **place-based appraisal techniques**, as outlined in the DfT's report *Capturing Local Context in Transport Appraisal (2021)*. This approach integrates local or regional social, economic, and environmental factors into the strategic case, enabling a more nuanced understanding of how transport schemes contribute to local resilience. Case studies such as the Sunderland Strategic Transport Corridor and the Newhaven Port Access Road in the report illustrate how scenario planning, sensitivity testing, and wider economic impact modelling can be used to reflect local vulnerabilities and inform robust decision-making and this could be considered further in a resilience context.

3.2.4 Workforce Resilience

To assess and build workforce resilience, methods include **skills gap analysis**, **scenario planning** to model workforce capacity under stress conditions, and training metrics to evaluate investment in competencies related to climate adaptation and digital infrastructure, as outlined in DfT's *Climate Adaptation Strategy for Transport (2025b)*, *Future Skills Needs across the Transport Sector (2024b)*, and the *Transport Infrastructure Skills Strategy (2016a)*. **Diversity and inclusion tracking** is also used to measure adaptability through demographic resilience and inclusive recruitment practices. These approaches are covered as part of the Rail Delivery Group's organisational resilience tool (Rail Delivery Group and PA Consulting, 2025a).

Key Findings

- Transport resilience appraisal has covered **multi-dimensional domains**, including economic, physical infrastructure, social, and workforce areas of resilience. The **Three Dividends of Resilience** (avoided losses, economic benefits, social/environmental gains) offers a consistent structure for evaluating resilience across all dimensions.
- Resilience appraisal is increasingly formalised through **mixed-method appraisal approaches**, enabling proportional analysis of shocks, stresses, and adaptive capacity.
- **Route resilience** focuses on strengthening individual corridors or assets against disruption, using tools like iRAP and the Route Review Tool to guide targeted interventions.
- **Network resilience** emphasises system-wide continuity, redundancy, and multi-modal alternatives, supported by advanced modelling and interdependency mapping.
- **Local and regional** resilience is critical for frontline response to climate events, with Local Resilience Forums (LRFs) coordinating emergency planning and community support. Operational tools like Early Warning Systems (e.g. LEWS) enhance local resilience by enabling proactive risk management, though formal appraisal metrics are still developing.
- **Workforce resilience** underpins system adaptability, assessed through skills gap analysis, scenario planning, and inclusive recruitment to ensure capacity under stress conditions.
- **Broad value recognition** is critical: resilience appraisal should capture system interdependencies, value chains, and critical components, not just isolated impacts, ensuring that transport investment strengthens adaptive capacity and operational continuity at every level.

3.3 Appraising Resilience in Cost Benefit Analysis (CBA)

Sections 3.1 and 3.2 highlighted how the appraisal and assessment of resilience in a transport context has drawn on a range of analytical frameworks. Given its centrality to economic appraisal, this section focuses on Cost Benefit Analysis (CBA) and the specific costs and benefits that have been appraised from resilience improvements in a transport context. It sets out the cost and benefit categories that have been captured inside and outside of the current TAG framework and examines how this assessment might overlap with other impact categories (such as reliability and option value). This section seeks to address the following research questions:

Key research questions:

What costs and benefits have been evidenced from improvements in resilience in a transport context?

How far do these overlap with existing impacts (e.g. reliability and option value)?

Which resilience impacts have been appraised quantitatively, and which qualitatively?

3.3.1 Costs

Investing in resilience involves both upfront and ongoing costs (ITF, 2024). These may include **capital expenditure** on infrastructure and other resilience interventions, and **operational costs** for maintenance and monitoring.

The modelling of capital and operational costs is intrinsically inter-related in the context of transport appraisal and requires an understanding of **whole life costs**. For instance, when appraising the optimal level of maintenance spend for maintaining a safe road surface condition, additional short-term resurfacing spend to improve the resilience of the pavement asset may lead to reduced maintenance spend in the future. *The Transport Resilience Review* commissioned by the DfT in response to the 2013–2014 winter storms emphasised the need for proactive investment to avoid escalating maintenance and repair costs (DfT, 2014). Similarly, the CIHT report on delivering a resilient transport network stressed that failure to invest in resilience could lead to significant infrastructure failures and related costs (CIHT, 2021). National Highways has modelled the relationship between these cost components as part of its asset condition modelling – see [Case Study 16](#), below.

Béné (2013) argues that the costs of resilience should go beyond financial expenses to include wider costs on society. The paper categorises these costs into three types:

- **Anticipation costs:** Investments made before a shock to prevent or prepare for it
- **Impact costs:** Immediate costs incurred during the disruption
- **Recovery costs:** Expenses related to recovery, adaptation, and transformation after the shock.

This mirrors other UK government appraisal methods – for example, the Home Office (2018) applies a similar structure to assess the costs of crime, covering anticipation, consequence, and response costs (Brand et al, 2005).

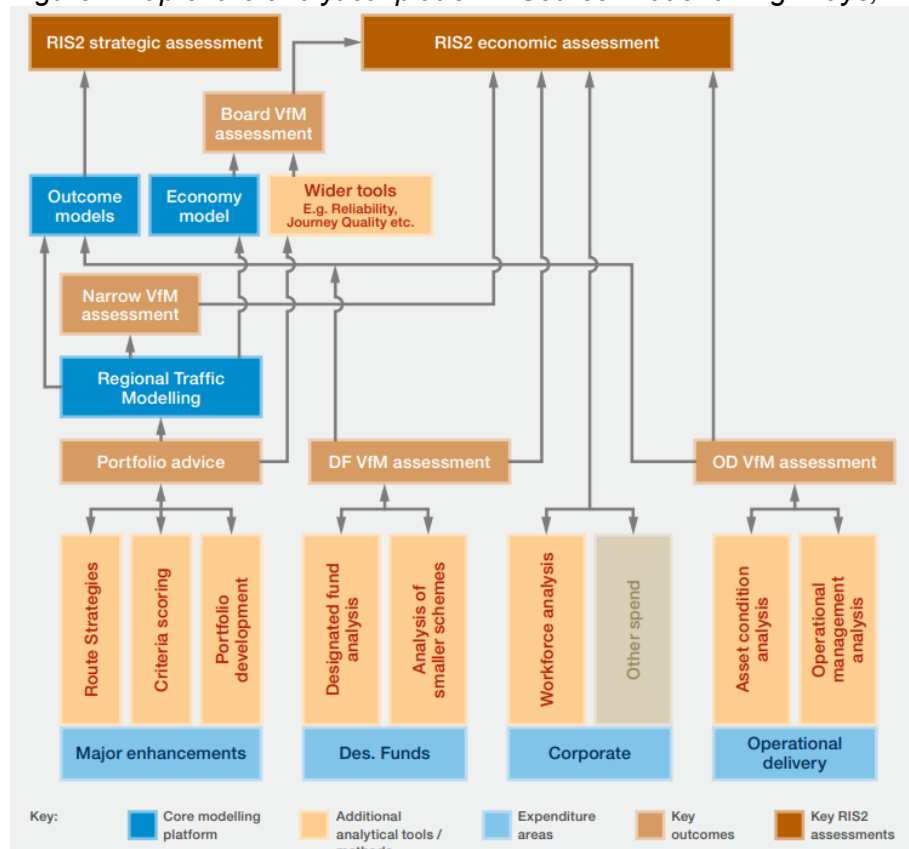
In Cost Benefit Analysis in line with TAG, anticipation costs likely reflect **known costs to the broad transport budget** and would likely be captured as a public accounts impact on the costs side of the appraisal. In contrast, if Impact and Recovery Costs are **not certain and extend beyond the broad transport budget**, these types of wider costs would be captured on the benefits side of the appraisal. Given the distinctive nature of the costs relating to resilience, there is the potential for cost guidance for resilience interventions to be factored into TAG.

Case Study 16

Asset Condition Modelling and Investment Appraisal for RP2

To support investment planning for the second Road Period (RP2: 2020–2025), National Highways developed an appraisal methodology to assess asset condition as part of an overarching analytical platform to prioritise maintenance and enhancement strategies.

Figure 7 Map of the analytical platform. Source: National Highways, 2017.



Asset condition tools (such as the Pavement Investment Tool) were used to model the condition of assets by comparing historical deterioration trends with current asset data. This enabled the projection of future asset performance under a ‘Do Nothing’ scenario providing a baseline for understanding long-term risks to network condition.

A **‘Do Minimum’ level of asset condition** was defined for RP2, informed by both technical and commercial expertise and was calibrated to reflect the expected impact of the major enhancement portfolio planned for the period (aligning maintenance strategies with broader network improvements).

Beyond this minimum condition level, further analysis was conducted to explore **‘Do Something’ improvement options**. These included upgrading construction materials and optimising for **whole-life cost efficiency**. Highways England applied the Highways Maintenance Appraisal Tool (HMAT) to quantify potential user benefits from these options such as reduced vehicle operating costs, improved journey times, and enhanced safety outcomes.

Overall, the Operations, Maintenance and Renewals spending for RP2 was assessed by DfT to be ‘Very High’ Value for Money (Department for Transport, 2020). For example, this analysis concluded that greater levels of repairs would be required for some roads if repairs were delayed or postponed slowing down traffic. There would also be costs to the user from slower and longer journeys as a result of maintenance works. This analysis evidenced the case for a higher level of upfront maintenance spend.

Where detailed asset data or historical trends were unavailable, National Highways applied risk-based modelling techniques and committed to addressing data gaps through targeted data collection and validation. This enabled all asset types to be assessed consistently, even in the absence of complete datasets.

3.3.2 Benefits

As seen in section 3.2, the financial cost of additional resilience to government must be balanced against the future 'dividends' that this spending delivers – both the avoidance of potential losses from shocks, and wider benefits in stable period.

TAG Benefit Categories

Addressing the nuances of transport appraisal requires these dividends to be examined in the **context of TAG benefit categories**. TAG assesses benefits at three levels:

- Level 1 (Direct User Benefits): Includes impacts which assume fixed land use (such as time savings and safety gains) and excludes wider economic impacts.
- Level 2 (Wider Economic Impacts): Encompasses journey time reliability and certain wider economic impacts that assume fixed land use (such as static agglomeration effects and labour supply effects).
- Level 3 (Dynamic Economic Impacts): Covers analysis where land use change is quantified (such as dependent development) or where dynamic, longer-term or structural economic changes have been evidenced through supplementary economic modelling.

ITF (2022) explains how in the short term, transport disruptions can affect passengers, workers, and service providers (i.e. Level 1 benefits). Over the long term, impacts can ripple through supply chains, local economies, and ecosystems (i.e. Level 2 or Level 3 benefits).

In theoretical terms, this means considering not only the **direct effects on journey times** but also understanding how improvements in resilience can deliver broader value by **reducing economic, social, and environmental costs** associated with these disruptions. A conceptual framework for how these impacts can be applied and appraised in practice is set out in Section 4.2.3.

For example, upgrading a flood-prone rail line may reduce delays (Level 1), support regional productivity by maintaining connectivity (Level 2), and enable long-term economic transformation in vulnerable areas (Level 3). The TAG framework encourages practitioners to consider these wider impacts when appraising transport investments, including where interventions can mitigate inequalities (demonstrated through place-based analysis). This is explored further in Section 0.

In practice, there are very little existing TAG appraisal evidence of calculating resilience impacts. Rather than adjusting Level 1 or Level 2 impacts, these appraisals have sought to capture resilience as a Level 3 impact – for example, The Lower Thames Crossing (2022) DCO appraisal, set out in [Case Study 17](#). Resilience was assigned as a Level 3 impact given the novelty and uncertainty around its estimation as well as the significant required computational effort to quantify resilience impacts. Broader HMG appraisal guidance is increasingly recognised the importance of accounting for **non-monetised impacts** when reaching Value-for-Money conclusions.

[Case Study 17](#)

Lower Thames Crossing (2022)

The economic appraisal accompanying the DCO of Lower Thames Crossing (LTC) incorporated resilience as a Level 3 impact category. The appraisal notes how disruptive incidents at the existing Dartford Crossing can last longer than six hours and the resilience appraisal reflected the ability of LTC to reduce the probability of, and manage and recover from, these long duration impacts. A qualitative appraisal was developed based on four different types of resilience. These are: event resilience, weather resilience, asset management and full closure.

Impacts assessed included:

- accidents (these can result in long delays as the Police determine when the road reopens)
- journey time reliability (where journey times varied due to incidents of all types lasting less than 6 hours in duration)
- planned maintenance works (some of these works involved full night-time closures of the Dartford tunnels)
- and option value benefits (this assessed the benefit for drivers of having another option to cross the Thames even if they did not use it).

The impact of LTC on resilience is driven by changes to: the likelihood of an incident occurring, the ability of the SRN to handle an incident while it is ongoing, and the ability of the SRN to recover from an incident more quickly.

The appraisal found that LTC will have a positive resilience impact through:

- **An increase in event resilience:** LTC's modern design and the lower number of vehicles using the Dartford Crossing will cause traffic to redistribute resulting in fewer incidents across the Lower Thames area. In addition, the additional network capacity will enable the network to recover more quickly from incidents and provides a partial diversionary route if incidents occur on the Dartford Crossing.
- **An increase in weather resilience:** During periods of high winds which can close the QEII Bridge, LTC provides road users a more weather resilient alternative route than the Dartford Crossing.
- **An increase in asset management resilience:** LTC enables the maintenance regime for Dartford Crossing to be optimised and less road users being impacted by major renewal work at Dartford Crossing.
- **An increase in full closure resilience:** In the event of a catastrophic closure of the Dartford Crossing, LTC preserves trip making across the Thames east of London without major diversions.

However, it is important to note that, while the LTC is intended to ease congestion at Dartford by adding capacity across the Thames, it hasn't been designed to act as a backup route during a major incident. Limited slip road capacity and single carriageway connections to the A2 mean it won't effectively divert traffic in emergencies. As LTC traffic grows, it will quickly reach capacity, and any major incident at Dartford could cause congestion to spread across both the M25 and A2 corridors. Although LTC may help some vehicles cross the river, its overall impact on resilience remains uncertain.

Avoided losses

In the detailed assessment approach proposed by PA Consulting (2024d) for measuring economic resilience, the avoidance of large-scale losses for individuals, businesses, the economy or wider society is argued to have a positive impact on social welfare and are analysed through an 'expected value' framework where the expected loss is calculated by multiplying the potential loss by its likelihood. Impact and likelihood can be influenced either by addressing the underlying threat/risk, or the exposure and vulnerability to these threats/risks (see below).

Driver	Description	Effect on expected loss
Underlying threat or risk	Eliminating or reducing the likelihood of the threat or risk to resilience occurring.	Reduced likelihood
Exposure to threat or risk	Reducing the presence of economic agents – organisations, institutions and individuals – that could be adversely affected by threats or risks to resilience.	Reduced potential loss
Vulnerability to threat or risk	Reducing the propensity of economic agents to suffer adverse effects when impacted by threats or risks to economic resilience through increasing their capacity to absorb shocks through increased robustness or redundancy , for example. Improved adaptive capacity can support the economy to suffer less during shocks and recover quicker, reducing vulnerability.	Reduced potential loss

Avoided losses – Capturing Economic Resilience in HMT Green Book Value for Money Assessments (2025)

The stylised model (shown below) presents system performance over time to illustrate the potential impact of avoiding losses in a system. Key features include:

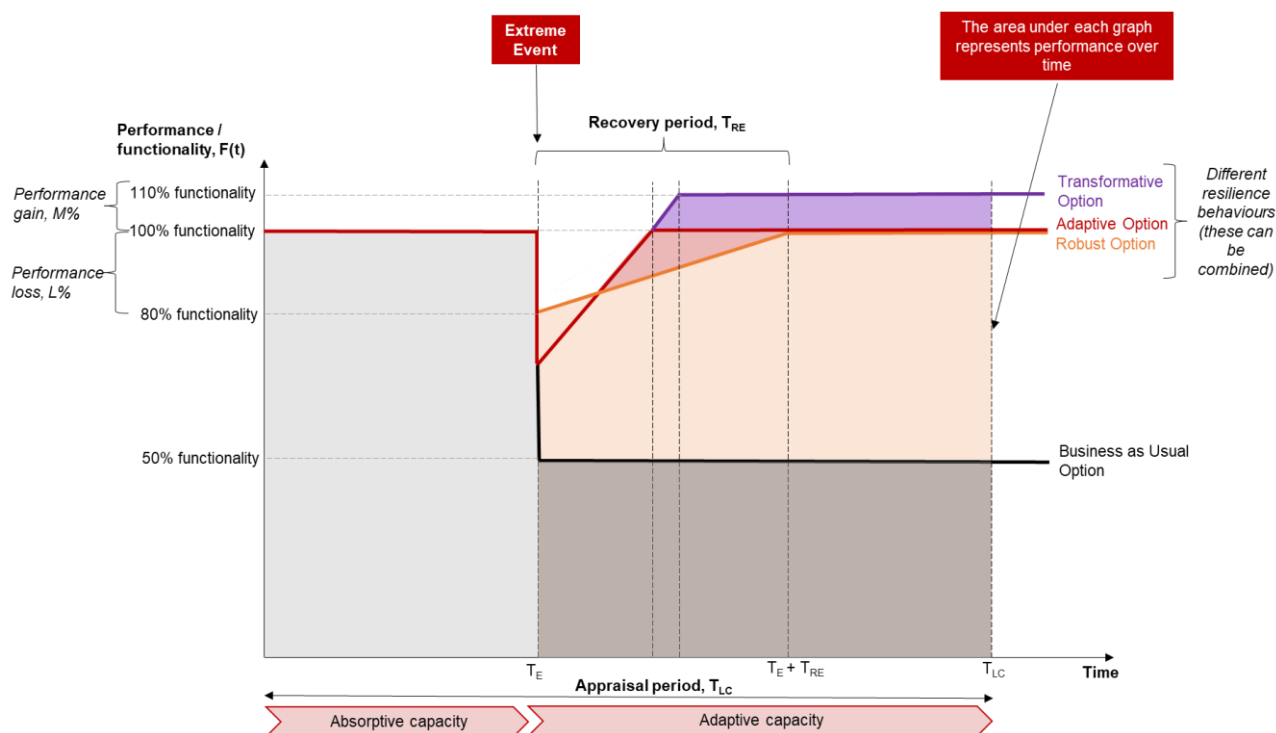
- A sudden drop in performance at a shock event
- Recovery trajectories for Business-as-Usual (lower resilience) and resilience interventions (higher robustness or faster recovery)
- The area under the curve for each option representing the overall system performance (or system resilience) during the appraisal period.
- Performance is plotted as percentage functionality, demonstrating how robust, adaptive, or transformative options affect recovery after a shock.

Calculating the 'avoided loss' involves mapping the performance trajectory of the system under Business-as-Usual (Do Minimum) and Resilience Options (Do Something), then calculating the difference in "area under the curve". Economic appraisal concerns the incremental avoided loss impacts identified when moving from the Do Minimum to the Do Something.

When **risk probabilities can be robustly estimated**, there is the potential to include avoided loss impacts in Net Present Social Value (NPSV) analysis through an expected value framework: potential loss multiplied by the likelihood of the risk materialising.

When **risk probabilities cannot be robustly estimated**, possibly due to reasons explained in Section 2.3.7, other uncertainty or risk-based approaches may be required (see Section 3.4).

Figure 8. Conceptual model for calculating Resilience and Avoided Losses. Source: PA Consulting.



Avoided losses in a transport context

The *National Highways Resilience Technical Annex (2022a)* can be seen as a more detailed potential application of the avoided loss framework within a transport context – where the 'avoided loss' in question is avoiding potential accidents and journey time reliability impacts. The approach covers both route and network resilience concepts discussed in Section 3.2 and involves running a Regional Traffic Model (RTM) to assess the impact of major incidents (that are beyond the remit of standard 'reliability assessment' – see Section 3.3.3). The impact of the incidents on user journeys is modelled under both "Do Minimum" and "Do Something" scenarios. The results are then monetised using Transport User Benefit Appraisal (TUBA), allowing the change in user journey times to be quantified. Further information is provided in [Case Study 18](#), below.

Case Study 18

National Highways: Resilience Technical Annex (2022a)

The Resilience Technical Annex focuses on evaluating the economic benefits of road schemes that **enhance the network's ability to recover from major disruptions**. This is defined as planned or unplanned **incidents lasting more than six hours**. The methodology is divided into two strands: route resilience and network resilience.

Route resilience is appraised in four key steps:

1	Evidence is gathered from historical incident data and operational practices to understand how major events (e.g. accidents, closures) are currently managed.
2	Scenarios are developed using historical data and hypothetical risks to reflect potential future incidents and their expected frequency.
3	Traffic modelling is conducted by removing affected links from the network and simulating the impact using inter-peak or average daytime matrices. This includes running both "Do Minimum" and "Do Something" models with and without incidents to assess the scheme's effect on recovery.
4	Results are appraised using TUBA , applying annualisation factors that combine incident frequency and duration. If the scheme alters the likelihood of incidents, separate TUBA runs are required for each case.

For **network resilience**, the methodology follows a similar structure but focuses on how the scheme helps the broader network cope with disruptions elsewhere. Evidence is collected on incidents in surrounding areas, and "what if" scenarios are constructed to simulate closures of nearby routes. These are modelled using the same traffic simulation techniques, but only the "With Incident" cases are needed, as the scheme does not influence the frequency of external events. TUBA is used to compare Do Minimum and Do Something outcomes, similarly applying annualisation factors to reflect incident characteristics.

Both approaches rely on **traffic modelling tools like SATURN** (Simulation and Assignment of Traffic to Urban Road Networks) and exclude variable demand modelling to better reflect short-term disruption impacts. Generic data tables are provided to support early-stage appraisals where local data is unavailable, offering incident frequencies and durations by region and type.

Whilst this provides a valuable theoretical model to date no publicly available economic appraisals have deployed this approach in analysis of transport schemes. Studies such as Ganin et al (2017) also focus on the impact on journey times, whilst other studies highlight how avoided loss calculations can extend to wider economic impacts (e.g. beyond Level 1 benefits and into Level 2 and Level 3 benefit categories). For example, DfT (2016b) seeks to quantify wider economic impacts through a GDP approach in TAG Unit A2.1, similar to attempts by Kurth, Ali et al (2020) in the US.

Building on these approaches, Zhang et al. (2023) shift the focus from transport performance alone to its wider economic implications. Using an integrated **Computable General Equilibrium (CGE)** model, they capture how disruptions propagate through labour markets, goods supply chains and household consumption, ultimately affecting regional and national GDP. The study introduces the **Economic-based Network Resilience Measure (ENRM)**, which evaluates resilience by integrating economic performance over the disruption and recovery phases. ENRM is calculated using **Equivalent Variation (EV)**, a monetary measure of changes in household utility compared to a baseline scenario, allowing analysts to estimate **avoided welfare losses**, which represent the economic value of preventing declines in consumption and production during shocks. To optimise resilience investments, Zhang et al. apply a **bi-level optimisation model**, where the upper level determines the allocation of investment to minimise ENRM and total costs, while the lower level simulates equilibrium in transport and economic systems to reflect behavioural responses. Their findings highlight that resilience interventions can avert significant GDP contraction under severe disruption scenarios, with benefits extending beyond transport reliability to include sustained economic activity and reduced recovery costs. Meaney et al. (2016) use similar top-down macroeconomic analysis, demonstrated through the 2010 Eyjafjallajökull ash cloud event, to evidence how major disruptions impose substantial economic losses across passengers, freight, tourism, supply chains, and productivity. This approach provides decision-makers with a framework to evaluate

trade-offs between investment costs and system-wide economic benefits, reinforcing the case for resilience as an enabler of long-term growth and stability.

Their work presents two structured quantitative approaches for resilience valuation: an **opportunity-cost method**, applied to the Dover–Calais disruption, capturing retention, diversion and suppression behaviour; and a **top-down macroeconomic analysis**, demonstrated through the 2010 Eyjafjallajökull ash-cloud event. Together, these studies reveal how major disruptions impose substantial economic losses across passengers, freight, tourism, supply chains, and productivity

Co-benefits: economic benefits and social and environmental benefits

Wider benefits that occur in non-emergency times need to be examined outside an avoided loss, expected value framework.

PA Consulting (2024d) developed a generalised Theory of Change model for interventions that seek to improve economic resilience (see Figure 9). Theories of Change are a form of logic model that maps causal links between interventions and the resultant outputs, outcomes and impacts. The Theory of Change demonstrates how **economic benefits and social and environmental benefits can be caused by a resilience or security intervention**.

The Theory of Change model can equally apply to where resilience is more an indirect or consequential impact (e.g. from an infrastructure project targeting other primary objectives). For example, a road-widening scheme aimed primarily at reducing congestion may also enhance network redundancy, thereby improving resilience. The model can identify the causal pathways from the intervention to resilience benefits explicitly.

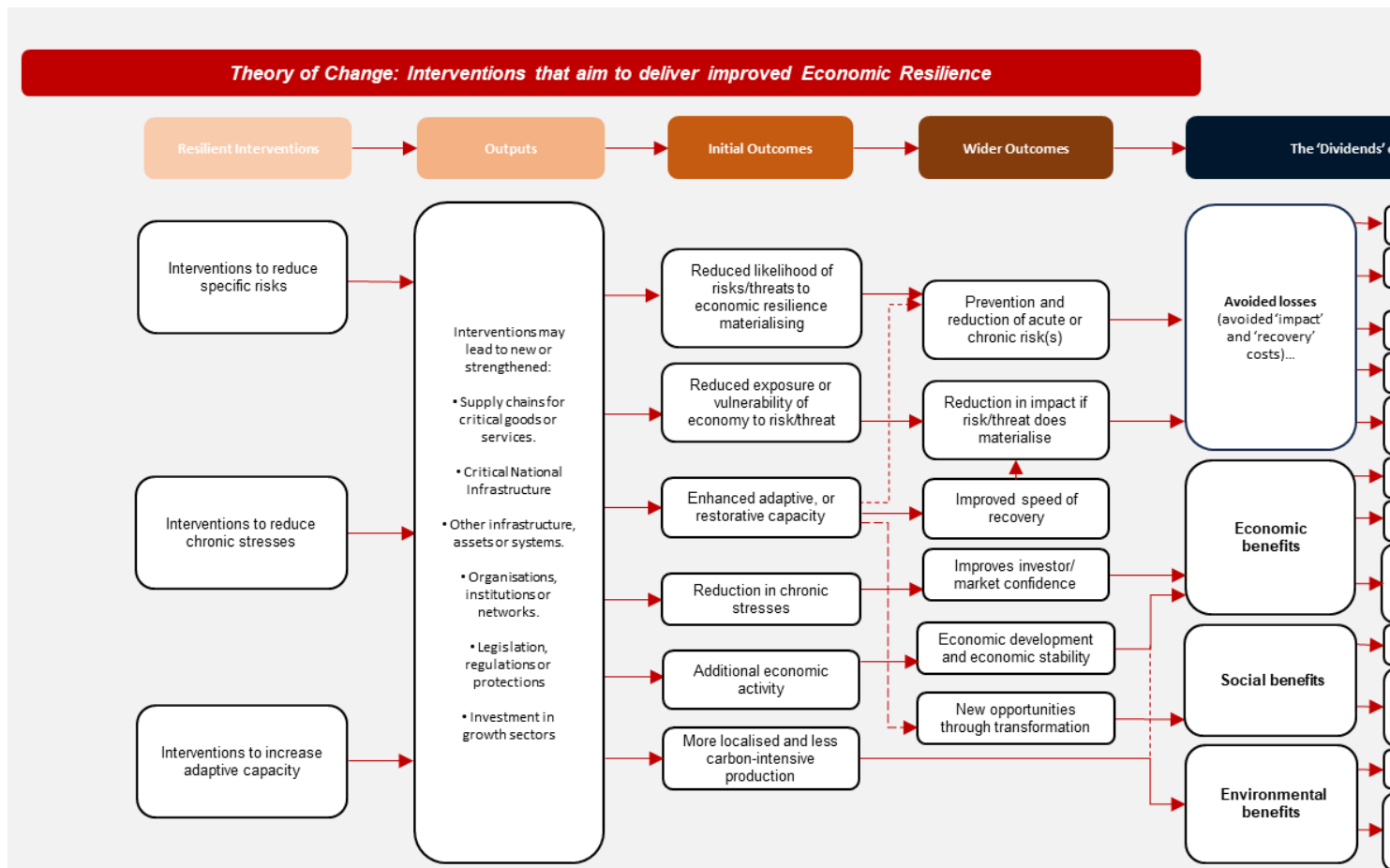
In a transport appraisal context, it is most likely that these types of benefits are already being considered in the appraisal through assessment of other Level 1, Level 2 and Level 3 benefits within TAG. Given the **significant existing literature and methods covering the appraisal of economic, environmental and social impacts**, these are not examined in further detail in the remainder of this review.

Distributional considerations

Resilience interventions may not affect all users equally. **Disadvantaged groups**, such as those in rural or poorly connected areas or without access to alternative transport modes, **face greater exposure to risk** and have fewer resources to respond or recover (Social Market Foundation, 2023). Social resilience factors, including community capacity and access to services, significantly influence how individuals experience and cope with disruption (Transport for the North, 2023). Consequently, widespread risks can lead to disproportionate outcomes for vulnerable groups when acute shocks occur. Appraisal may therefore need to assess not only the total quantity of benefits from improved resilience, but also the **distributional impacts of these interventions**

Incorporating distributional analysis into resilience appraisal helps decision makers avoid **unintended consequences** that could exacerbate existing inequalities. It ensures that interventions are not only effective in scale but also equitable in impact, recognising that resilience is not just about infrastructure but also about people's ability to access, use, and benefit from transport systems under stress.

Figure 9. 'Theory of Change' model for identifying strategic benefits from improving resilience.



Other Impacts

The TAG framework does not largely consider '**subjective wellbeing**' impacts; however, life satisfaction and self-reported utility are relevant to note in forming an economic appraisal framework of resilience in a transport context. It should also be noted that transport benefits from additional resilience may be **relevant in appraisal contexts outside transport**. For example, the *Surface Water Future Risk and Investment* report (Sayers and Partners, 2022) which finds that benefits of improved surface water management are not limited to direct flood damage reduction. They also include wider economic, social, and environmental co-benefits, such as improved water quality, ecosystem services, and **reduced disruptions to transport**, health, and business operations.

3.3.3 Overlap of Resilience Appraisals with Reliability

Distinguishing Resilience and Reliability

Section 2.1.4 distinguishes **reliability from resilience**. Reliability refers to a system's ability to function consistently and predictably under normal operating conditions. Resilience, on the other hand, concerns a system's capacity to withstand and recover from significant stress or disruptions. While a transport system may be reliable in day-to-day operations, it can still be vulnerable to unexpected events if it lacks resilience.

Reliability Appraisal in TAG

Chapter 6 of *TAG Unit A1.3 User and Provider Impacts* (Department for Transport, 2025b) develops the concept of reliability within transport appraisal by defining it as the **variation in journey times that individuals are unable to predict**. This form of uncertainty, referred to as journey time variability (JTV), encompasses both day-to-day variability (DTDV), which arises from recurring congestion typically experienced at similar times each day, and non-recurring disruptions such as accidents, breakdowns, and operational anomalies. These sources of variability are treated distinctly from predictable fluctuations in demand, such as those associated with time-of-day or seasonal patterns, which are assumed to be anticipated by users and therefore excluded from the reliability definition.

The appraisal of reliability applies across all road types and uses a **reliability ratio**, defined as the value of the standard deviation of travel time divided by the value of average travel time. The recommended value for car journeys is 0.4, based on stated preference research conducted for the DfT. This ratio reflects the **relative disutility of unpredictable delays compared to average journey time**, capturing the behavioural response of users to variability in travel conditions. The ratio is embedded in the MyRIAD tool, which estimates monetised reliability impacts for different road types. For urban roads, there are no established methods for modelling journey time variability, as delays are driven primarily by junction performance rather than link capacity. Ideally, locally calibrated models should be employed to estimate standard deviations, incorporating area-specific data and travel patterns to improve accuracy.

For single carriageways outside urban areas, reliability impacts can be modelled using the MyRIAD tool, which estimates the effects of traffic variability on journey times. Where MyRIAD or similar modelling is not applied, reliability is assessed using the **concept of 'stress'**, defined as the ratio of annual average daily traffic (AADT) to the Congestion Reference Flow. Stress serves as a proxy for reliability, with higher stress levels indicating reduced reliability due to flows approaching or exceeding network capacity. This approach provides a broad indication of reliability impacts in contexts where detailed modelling is not feasible.

In the case of unscheduled journeys on motorways and dual carriageways, TAG guidance indicates that incidents are generally the dominant source of unpredictable delay, particularly when traffic demand remains below capacity. In such contexts, delays caused by congestion unrelated to incidents are typically captured within standard journey time forecasts, whereas **incident-related delays require separate treatment**. MyRIAD is a bespoke JTV valuation tool used to estimate the reliability benefits of transport interventions, which quantify reductions in both incident-related and congestion-related variability. Although reliability benefits are excluded from the Analysis of Monetised Costs and Benefits (AMCB) table used to calculate Net Present Value (NPV) and the conventional Benefit-Cost Ratio (BCR), they are reported in the Appraisal Summary Table (AST) and contribute to the Adjusted BCR. Reliability benefits are categorised as Level 2 impacts because there is an emerging, but not yet well-established, consensus on how to estimate them. Consequently, their monetised values are reported alongside other Level 2 impacts such as wider economic impacts under static clustering conditions.

In the case of scheduled journeys, such as those undertaken by rail or public transport, reliability is typically measured in terms of **lateness**, defined as the difference between actual and timetabled arrival times. The appraisal focuses on both the **average lateness and its variability**, with the former the usual focus and the latter expressed as the standard deviation of lateness. TAG recommends valuing average lateness at 2.5 times the value of in-vehicle time and applying a reliability ratio of 1.4 across all public transport modes. These values are derived from the Passenger Demand Forecasting Handbook (PDFH) and supported by empirical studies such as Batley and Ibáñez (2013), which provide a robust evidence base for the monetisation of reliability impacts. The **higher reliability ratio for public transport reflects the greater disutility associated with lateness in scheduled services**, where missed connections and rigid departure times amplify the impact of variability. In contrast, car users typically have greater flexibility in departure time, which mitigates the perceived cost of journey time variability.

The valuation of reliability within UK transport appraisal is underpinned by a substantial body of empirical research. Bates et al. (2001) set out the theoretical and empirical basis for valuing journey time variability, including the foundations of the reliability ratios used in appraisal. Subsequent evidence from Batley and Ibáñez (2013) reinforces this framework through modern stated-preference estimation of journey time risk for rail travellers. Separately, Batley et al. (2017) reformed the valuation of travel time savings by replacing the cost-saving approach with a willingness-to-pay framework, supported by extensive stated-preference data and advanced choice modelling. Internationally, Dubernet and Axhausen (2019) provide Germany's first official valuations for travel time and reliability. While they do not propose alternative reliability ratios, their study reinforces the UK's approach.

National Highways Distinction between Reliability and Resilience Appraisal

National Highways distinguishes reliability from resilience based on both the duration and nature of a disruption. In appraisals using the MyRIAD tool, disruptions lasting less than six hours are typically classified as reliability issues, while those exceeding six hours are treated as resilience impacts (National Highways, 2022b)⁶. This threshold is drawn from MyRIAD guidance, which assumes that **incidents**

⁶ See Economic Appraisal Report (EAR) for the Lower Thames Crossing DCO.

lasting more than six hours trigger behavioural responses such as rerouting or trip cancellation, going beyond day-to-day variability and therefore falling under resilience (National Highways, 2023). The Myriad User Manual states: *“To avoid overstating delays as a result of this simplification, MyRIAD also caps the build-up duration of incidents to a maximum of 6 hours”*.⁷

The **six-hour cut-off provides a pragmatic boundary** to separate short-term variations in travel times from more severe disruptions, helping to avoid double-counting benefits.

In the Lower Thames Crossing (LTC) Development Consent Order (DCO) appraisal, resilience benefits were not monetised because the resilience appraisal approach set out in the Technical Annex of the Appraisal Manual had not yet been published. However, the LTC appraisal did identify different types of resilience impacts, including severe weather events, major incidents, and network closures. While incidents exceeding six hours are relatively rare, their monetised value is naturally small due to low probability, even though their consequences can be severe. Capturing higher values for resilience may require further evidence on the “Willingness to Pay” to avoid catastrophic disruptions. This could also include valuing the insurance-like benefit and peace of mind that comes from being protected against such events, even if they are unlikely.

An example that supports the rationale behind the six-hour cut-off is the Larcom et al. (2017) study, discussed in section 2.3.3, which examined commuter behaviours during the London Underground strikes in February 2014. Despite lasting less than 48 hours, the authors found that many commuters permanently changed their travel routes after being forced to experiment with alternatives. This behavioural shift persisted long after normal service resumed, providing empirical support for the idea that **lengthier disruptions can lead to structural behavioural change**.

However, while the six-hour threshold is a useful tool for distinguishing reliability from resilience, the use of a fixed duration may oversimplify the complex nature of disruption impacts, particularly when behavioural responses vary not only by duration but also by context, severity, and user type.

Critiques of National Highways appraisal framework, raised by the DfT, highlight several wider analytical challenges. Firstly, there is the **issue of time inconsistency in stated preference methods**, where individuals value disruptions differently depending on whether they have experienced them, leading to potential bias in valuation. Secondly, the reliance on expected value calculations may **fail to capture fat-tailed risks**, such as rare but catastrophic events, which are poorly represented in average-based models. Thirdly, the appraisal framework does not adequately capture the **insurance value** of resilience, the **additional benefit individuals derive from reducing uncertainty and gaining peace of mind** that severe disruptions are less likely to occur, even if this value is not reflected in direct cost-benefit terms. These critiques highlight limitations that suggest that current methods may underrepresent the full spectrum of resilience impacts, particularly in the face of uncertainty, behavioural complexity, and systemic risk.

3.3.4 Overlap of Resilience Appraisals with Option Value

Option Value in TAG

TAG Unit A4.1 Social Impact Appraisal (DfT, 2022b) defines option value as *“the willingness-to-pay to preserve the option of using a transport service for trips not yet anticipated or currently undertaken by other modes, over and above the expected value of any such future use.”* TAG identifies three core characteristics of option value: it arises **from uncertainty about future use**, it **exists independently of actual uptake**, and it is **influenced by individual risk aversion**. A key distinction in appraisal terms is that typically, reliability and resilience are assessed in the context of actual journeys undertaken and therefore relate to known or expected usage. Option value, by contrast, is not bound by certainty of future use as it captures the benefit of preserving transport availability for unanticipated or latent demand. This makes it particularly relevant in contexts where future travel needs are uncertain, and where **maintaining flexibility in the network offers reassurance and adaptability** beyond what is captured in conventional assessments.

⁷ This is confirmed by parameters recorded in the Global Constants tab within the MyRIAD software (2020 onwards) which constrains how MyRIAD assess the impacts of incidents whose duration exceeds 6 hours: 1) Constant ID9 specifies the maximum incident duration in seconds of 21,600 which is 6 hours. 2) Constant ID2 specifies the maximum link utilisation at 0.95. This effectively limits the traffic volume to a road's capacity at 95% and prevents very long duration queues from forming – meaning that average delays will remain lower than the maximum incident duration of 6 hours. These constraints apply to the core and sensitivity modelling. The Average Delay Threshold of 99,999 minutes quoted in the Manual no longer reflects the actual binding constraint, which is set to 6 hours through the parameters described above.

Although monetisation is possible in specific contexts, particularly for local rail and bus services in small communities, TAG recommends a qualitative approach in most cases, using a seven-point scale to reflect the magnitude of impact. Indicative household values are provided in the TAG Data Book (DfT, 2025h), with annual figures of £227 for rail and £115 for bus services (2023 prices), though these apply only to small-scale, localised services and should be sensitivity tested to avoid potential double-counting with non-use values. Non-use value refers to the benefit individuals derive from the continued existence of a transport service, regardless of any intention or ability to use it. While closely related to option value, the key distinction is that option value reflects the benefit of preserving the ability to use a service in the future (potential use), whereas **non-use value is entirely independent of use** and often reflects altruistic or existence-based motivations.

In appraisal, TAG advises focusing on the incremental change in option value resulting from a proposed intervention, rather than its absolute level. Catchment areas are used to estimate the affected population, providing a practical method for assessing the scale of impact. The guidance uses The Passenger Demand Forecasting Handbook (PDFH) for its provided catchment distances: 2 km for minor stations, 5 km for reasonably main stations, and larger catchments for free-standing towns. These catchments help estimate the number of households who may value the availability of a transport service, even if they do not currently use it. TAG Unit A4.1 outlines a qualitative scoring framework based on the number of households affected: over 1,000 households indicates a large impact, 250-999 households a moderate impact, 1-249 households a slight impact, and 0 households a neutral impact. Where possible, local knowledge should inform catchment definitions, accounting for factors such as service frequency, station accessibility, and urban or rural context. In cases where multiple stations are in proximity, overlapping catchments should be considered, with option value only lost if all relevant services are withdrawn. This approach enables a **proportionate and evidence-based assessment of option value impacts**, particularly in scenarios involving the introduction or withdrawal of transport services.

Empirical Studies on Option Value

Research by Laird et al. (2013) provides strong empirical evidence for including option and non-use values in transport appraisal, particularly for bus services. Their national and local surveys found that many households value services they do not regularly use, especially for unexpected or emergency trips. The estimated option and non-use value of the national urban bus network was £490 million annually, with low-income households placing higher value for evening and Sunday services. The study also showed that option use is driven more by transport-specific factors, such as car availability and service frequency, than by personal characteristics. Importantly, the monetary valuation of these benefits often exceeded the cost of subsidising services, supporting their inclusion in transport appraisal.

International studies on option value also support its inclusion in transport appraisal, such as Bondemark et al. (2021), who analysed housing prices in Sweden to estimate the value individuals place on having access to multiple transport modes. Hedonic pricing models work by decomposing the price of a good, such as a house, into the implicit values of its attributes (like number of rooms, location, and size), allowing researchers to infer the monetary value of non-market characteristics such as accessibility. Using a hedonic pricing model, they found that areas with higher modal substitutability, defined as the robustness of accessibility across different transport modes, were associated with significantly higher property values, even when total accessibility was held constant. Their findings suggest that households are willing to pay a premium for the flexibility offered by alternative transport options, reflecting the **insurance-like nature of option value**. Their approach offers a generalisable method for capturing option value through revealed preferences, complementing stated preference techniques and reinforcing its relevance in transport appraisal.

Distinguishing Option Value and Resilience

Option value in transport appraisal refers to the benefit individuals gain from having access to alternative modes, routes, or services, even if they do not use them regularly. **Closely linked to the concept of redundancy** explored in section 2.1.4, option value is fundamentally about the reassurance and flexibility that comes from knowing alternatives are available if circumstances change, such as during disruptions, changes in personal needs, or unexpected events. While resilience is typically assessed in the National Highways Appraisal Manual as the ability of the transport network to withstand and recover from **disruption affecting known or expected journeys**, option value captures the societal benefit of maintaining redundancy for unknown or latent demand.

By capturing the insurance benefit of redundancy, option value highlights why maintaining or investing in backup options is important, not just for operational continuity, but also for the confidence and adaptability it provides to users when future demand or conditions are unpredictable. Resilience and option value are linked in this way. **The same redundant links that create option value under uncertainty of journey purpose also contribute to resilience by mitigating losses and maintaining accessibility for known journeys during disruption.** In this way, option value complements resilience appraisal by broadening the scope of benefits considered, particularly in appraisal contexts where future travel patterns are uncertain or evolving. Further research could be undertaken to seek to further distinguish these impacts by valuing individual user's Willingness to Pay for resilience against acute shocks leading to long-duration delays (e.g. through stated preference survey methods).

The *Lower Thames Crossing Economic Appraisal Report* (National Highways, 2022b) demonstrates how option value and resilience can be incorporated into an economic appraisal consistent with TAG. Option value is treated as a Level 3 impact and is qualitatively assessed within the Appraisal Summary Table, contributing to the overall Value for Money assessment. It is scored positively, reflecting the value placed on having the option to use the new crossing in future, even by those who may not currently intend to do so. As per [Case Study 17](#), the LTC appraisal adopts a bespoke qualitative framework, with the overall conclusion being that the scheme is likely to have a positive impact on the resilience of the strategic road network.

Key Findings

- **Cost Benefit Analysis (CBA) remains central to appraising resilience** interventions in transport, allowing both direct and wider costs and benefits to be systematically analysed in line with TAG.
- The **costs of resilience** investment encompass upfront capital expenditures, ongoing maintenance and operational costs, the relationship between which is increasingly recognised within **whole-life asset management models**.
- **Benefits from resilience** improvements span avoided disruption costs, enhanced reliability, improved safety, and wider social and economic dividends. In theory, these impacts could cover Level 1, Level 2 and Level 3 impacts assessed in TAG.
- **Avoided loss modelling**, where system performance trajectories under risk and resilience scenarios are compared, could provide a potential framework for quantifying benefits such as reduced journey time delays, lower asset repair costs, and sustained economic activity. Whilst challenging, there may be potential for these avoided losses to be monetised in Net Present Social Value (NPSV) terms, when risk probabilities can be credibly estimated – an initial framework is explored in Section 4.
- **Wider resilience benefits** can overlap with established appraisal categories, especially journey time reliability, option value, and non-use value. Clarity is required to avoid double-counting.
- The **technical distinction between reliability and resilience** is operationalised via a six-hour disruption threshold in National Highways appraisal, a pragmatic rule to separate short-term variability (reliability) from longer, behaviour-changing shocks (resilience). However, this cut-off may not fully capture the spectrum of user responses or system impacts.
- Option value reflects the willingness to pay to preserve access to alternative routes, modes, or services **under uncertainty about future use**. It shares some conceptual ground with resilience, as both value the adaptability provided by redundancy.
- Appraisal methods **increasingly recognise wider social, environmental, and wellbeing** benefits from resilience interventions, such as improved health outcomes. Distributional analysis can also play a role in identify resilience interventions that deliver equitable benefits.

- **Empirical evidence and case studies** (e.g., Lower Thames Crossing, National Highways Resilience Technical Annex) show that robust modelling, scenario analysis, and explicit treatment of resilience within the appraisal framework can strengthen the Value for Money case for investment.
- Despite methodological advances, resilience impacts are still **underrepresented in appraisals**, particularly where risks are difficult to quantify, or behavioural responses are complex, highlighting the need for further guidance.

3.4 Examining Alternatives to Cost-Benefit Analysis

Despite its frequent use, CBA faces limitations in fully capturing resilience impacts, especially when benefits are long-term, uncertain, or difficult to monetise. In this section, we examine how CBA has been adjusted to better incorporate resilience considerations, or where alternative appraisal frameworks and policy tools have been deployed. This section seeks to address the following research question:

Key research question: *Are there any relevant alternatives to cost-benefit-analysis (e.g. resilience standards/cost effectiveness analysis or wider uncertainty toolkits)?*

Adjustments to Cost Benefit Analysis

Scenario-based CBA with ‘regret analysis’

Some practitioners have taken scenario-based CBA further through applying ‘regret analysis’ – for example, the US Department of Transportation’s Resilience and Disaster Recovery (RDR) Tool Suite applies this approach (US Department of Transport, Volpe Center, 2022). Regret analysis overlays CBA results by reflecting the potential downside of choosing one investment over another if future conditions differ from expectations. Instead of seeking to maximise the NPSV, it considers the “regret” a decision-maker might feel if a chosen project performs poorly under a particular scenario compared to the best-performing alternative. The conclusions for decision-makers can be multi-dimensional: recommending the option with (i) the lowest maximum regret (ii) the lowest average regret (iii) maintains a positive NPSV across most scenarios and avoids catastrophic regret. Regret analysis does not directly say whether the VfM is positive, but whether the highest expected NPSV option under CBA performs very badly under plausible scenarios. This approach helps identify projects that are not just optimal on average, but performs sufficiently well across a range of plausible futures.

Scenario-based CBA with breakeven analysis

Other practitioners have applied **breakeven analysis** as part of CBA to identify the conditions under which a transport project’s benefits would just outweigh its costs. This is particularly useful in resilience planning, where the probability and severity of future hazards are uncertain by allowing transport planners to ask how bad a future event would need to be for an investment to pay off. Argyroudis (2021) argues that transport authorities can use such breakeven analysis to inform the design thresholds for acceptable values of the resilience metrics, e.g. “maximum risk tolerances” or “viable minimum service levels” of the assets. Using threshold-based views of value, could help transport authorities rationalise investments in resilience even when precise risk probabilities are unknown.

Wider Approaches involving Resilience Standards

Resilience standards and strategic analysis as a policy tool

A growing line of thought in resilience planning centres on the use of **resilience standards** which defines **thresholds or performance criteria** that infrastructure should meet to ensure adequate preparedness and adaptability in the face of disruption. In an appraisal context, these standards can serve as a benchmark: rather than evaluating all possible outcomes, analysts can assess whether different project options meet or fail to meet the specified resilience threshold. This approach simplifies decision-making and aligns investment with strategic resilience goals. NIC’s 2020 *Anticipate, React, Recover* paper recommends that the government should publish a full set of resilience standards every five years, following advice from regulators, alongside an assessment of any changes needed to deliver

them. Following this, NIC (2024) says “*infrastructure operators argue that they cannot cost resilience until they understand what the target level of resilience is*”.⁸

CEN (2021) describes how relevant service and resilience standards in transport could be set without cost-benefit analysis. For example, the resilience standards could be **established in the Strategic Case as a Strategic Objective (SO) or a Critical Success Factor (CSF)**. In line with Green Book guidance, options that fail to meet a SO or CSF would be ruled out at short-listing stage before detailed CBA is undertaken.

Resilience standards and cost benefit principles

However, this raises a critical question: how should the appropriate resilience standard be set in the first place? The process of defining these thresholds whether based on risk tolerance, economic efficiency, or societal values for example, is complex and often underdeveloped. It is broadly acknowledged that **CBA frameworks can play an important role in determining the “right” resilience standard** – as a means of trading off the resilience benefits from higher standards and the costs that are involved in meeting such a standard. For example, in the context of health and safety standards, rather than using a strict CBA approach, the Health and Safety Executive apply a CBA approach grounded in the concept of “reasonable practicability”. This could provide a model for how appraisal can be used to define resilience standards in transport, where similar principles of risk tolerability and societal value apply.

Case Study 19

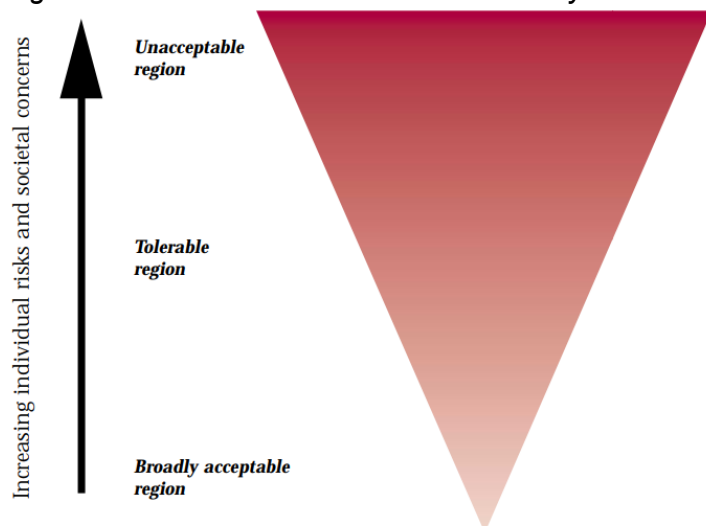
Reducing Risks: Protecting People – Health and Safety Executive (2001)

The HSE’s decision-making framework is built around the principle of tolerability of risk, which guides whether further risk reduction measures are justified. HSE applies an approach grounded in the concept of “reasonable practicability.” This involves weighing the costs of implementing safety measures against the benefits of reducing risks to health and life, with a key test being whether the cost is “grossly disproportionate” to the risk reduction achieved.

Risks are assessed within a three-zone model:

1. **Unacceptable region:** risks are intolerable regardless of benefits.
2. **Tolerable if ALARP (As Low As Reasonably Practicable):** risks may be acceptable if further reduction is not reasonably practicable.
3. **Broadly acceptable region:** risks are so low that no further action is typically required.

Figure 10. HSE framework for the tolerability of risk.



Appraisal involves both quantitative estimates (e.g. risk levels, potential fatalities and monetary valuations of these) and qualitative judgement.

Source: Health and Safety Executive (2001)

⁸ For example, NIC (2024) recommends that water companies should be asked to plan for a drought with a 0.2 per cent annual probability because proactive resilience (managing leakage and demand and building new supply infrastructure) would cost roughly half as much as reactive measures. This has enabled the water industries to assess options and propose costed programmes for achieving this standard.

System performance approaches in resilience can also inform standards through **criticality analysis which is agnostic of risk**. For example, understanding the most critical parts of a system involves analysing the impact of taking out that component. The cost of protecting that component (e.g. through a resilience standard) can be compared to cost of loss irrespective of risk.

Cost Effectiveness Analysis (CEA)

Often, CEA approaches are favoured over CBA to appraise options for meeting a specific standard that has already been defined. This might include whether proposed interventions meet a minimum threshold of resilience such as maintaining service continuity during extreme weather events or recovering within a specified timeframe after disruption. Through carefully defining “effectiveness”, CEA enables decision-makers to identify the most cost-effective way to meet a predefined level of resilience without requiring benefits to be monetised. In CEA, NIC (2024) states the importance of considering the system of standards as *“while individual standards may be affordable on their own, they may add incremental costs to the system as a whole”*.

Multi-criteria frameworks

Some literature advocates for the integration of CBA with multi-criteria frameworks. For example, IFT (2022) discusses complementary methods such as Multi-Criteria Analysis (MCA), particularly in the context of climate-related risks. These approaches allow for the inclusion of qualitative factors, equity considerations, and stakeholder preferences and could enable decision-makers to take a more rounded view of resilience, making the trade-offs between cost, risk, and social outcomes more explicit. Multi-criteria approaches are also common features of resilience “indicator and metrics” frameworks. The Green Book states that MCDA should only be undertaken as a complement to CBA or where monetisation of benefits is not feasible.

An adaptation of MCA in a resilience context was used in NIC’s *Reducing the risk of surface water flooding* paper (NIC, 2022) – adopting a ‘solutions hierarchy’ approach to rank drainage interventions with differing levels of scope. It prioritises maintenance optimisation, followed by above ground interventions, with below ground interventions (pipes and sewers) considered last because they tend to be more expensive, disruptive to install, and less effective at delivering co-benefits.

Advanced decision-making tools

Resilience appraisal is increasingly being supported by advanced decision-making tools. The Resilience and Disaster Recovery (RDR) Tool Suite (US Department of Transport, Volpe Center, 2022), for example is an advanced decision-support system developed to help US federal and state transportation agencies appraise and prioritise infrastructure investments in the face of natural hazards and climate-related risks.

Case Study 20

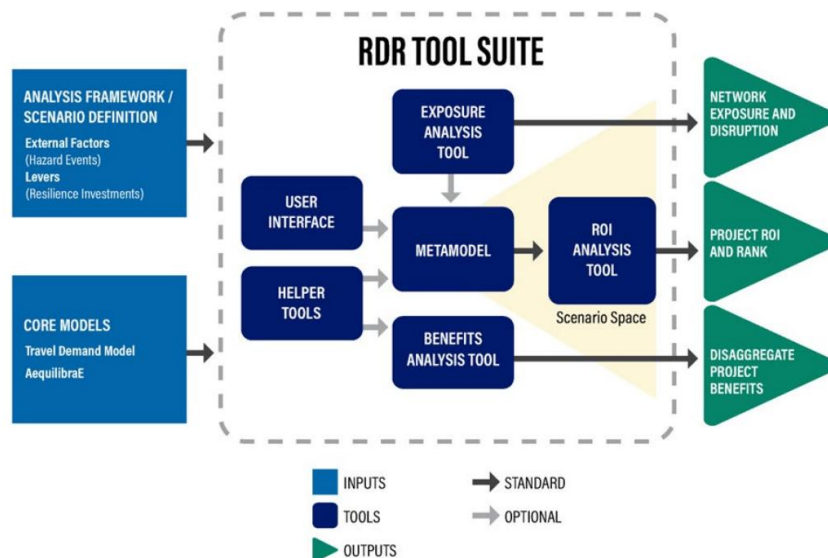
Resilience and Disaster Recovery (RDR) Tool

The RDR Tool operates under **conditions of deep uncertainty** using, using robust decision-making principles that accommodates varying levels of data availability and quality, making it particularly valuable for long-term strategic planning.

The metamodeling framework integrates hazard and exposure analysis, network performance and capacity loss estimation, and economic impact modelling. Outputs include an ability to rank projects based on their economic return on investment (ROI), and the user can select the appraisal framework: **CBA, CBA with regret analysis, or breakeven analysis**.

The CBA model factors in repair costs, faster recovery times, and enhanced roadway network connectivity. Users can either rely on default values provided by the tool or input customised data based on their own agency’s expertise, allowing for **context-sensitive appraisal**.

Figure 11. Indicative Framework. Source: US Dept of Transport Volpe Center (2025).



Combining multiple appraisal tools

Multiple appraisal frameworks can ultimately be used over the course of the development of a project. For example, Case Study 21 provides the example of the Exeter to Newton Abbot Geo-Environmental improvement, highlighting how resilience standards/targets, MCA and CBA has been used sequentially as part of the option identification and appraisal process.

Case Study 21

Exeter to Newton Abbot Geo-Environmental Resilience Study

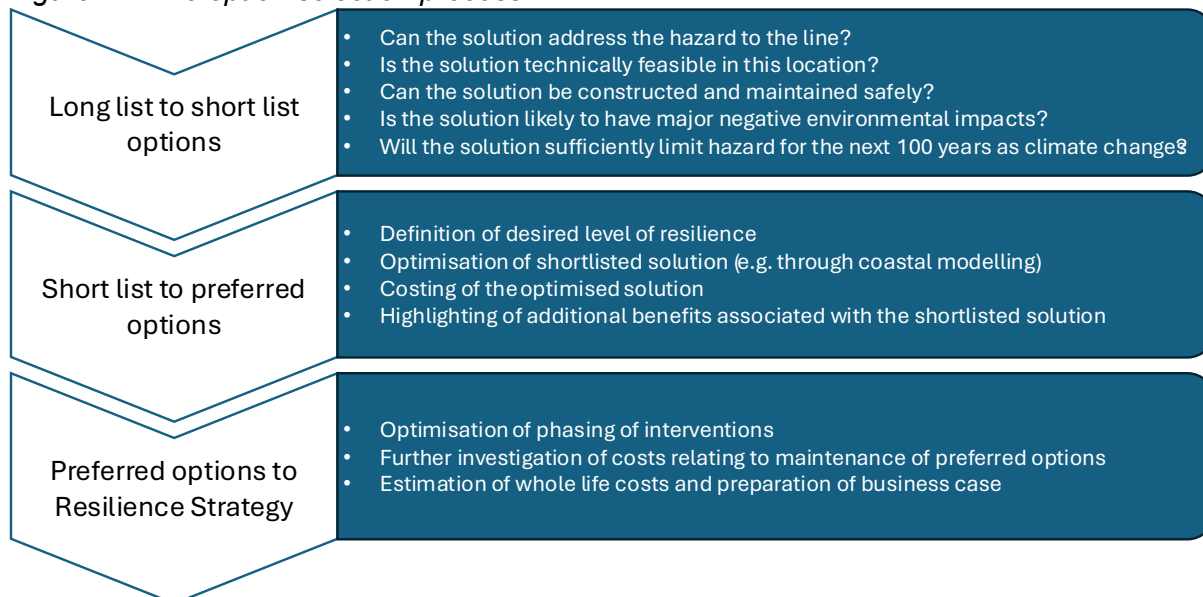
The Exeter to Newton Abbot Geo-Environmental Resilience Study outlines a comprehensive strategy to improve the long-term resilience of a critical railway line in Southwest England, which has historically been vulnerable to environmental hazards such as flooding, cliff erosion, and storm damage. The study was initiated following major disruptions in 2014, including a seawall breach and a significant landslide, which highlighted the fragility of the route and its importance to the regional economy.

The resilience appraisal approach was structured into three main phases:

Phase 1 focused on establishing a baseline understanding of the route's vulnerabilities. This involved reviewing historical failures, assessing future climate change impacts using UK Climate Projections (UKCP09), and analysing coastal and geotechnical conditions. The study **defined resilience targets** for different levels of disruption (extreme, severe, and moderate) with the aim of significantly reducing their frequency over the next century.

Phase 2 involved developing a wide range of intervention options across three asset groups: coastal defences, geotechnical stability, and rail infrastructure. Rail infrastructure improvements were considered but deemed insufficient on their own to achieve the desired resilience, so they were integrated into broader schemes. The options were appraised through a **multi-criteria filtering process** that considered technical feasibility, safety, environmental impact, and long-term effectiveness under climate change. Preferred options were selected based on their ability to meet resilience targets and deliver value for money. These were then incorporated into a phased Resilience Strategy aligned with Network Rail's funding cycles (Control Periods), prioritising high-risk areas for early intervention.

Figure 12. The option selection process.



Phase 3 finalised the strategy and developed the **CBA in line with TAG**. Recommending a preferred option with priority works scheduled for Control Periods 6 to 8 (2019–2034), and further interventions extending to CP18.

Frameworks for transport appraisal in Europe also highlight the value of integrating multiple analytical methods. The Conference of European Directors of Roads (2022) examines the ‘hybrid’ appraisal approach taken by Gühnemann, Laird, & Pearman (2012) to support the implementation of transport policies when prioritising road infrastructure investment projects. **CBA results are incorporated into an MCA framework** to retain strength of each method whilst offering decision makers a clear pathway to create an initial ranking of investment projects where the connections between all potential investments and the pursued policy goals are clear. This also enabled uncertainty to be integrated as an explicit assessment criterion rather than a qualitative overlay to CBA results. This hybrid approach might be valuable when evaluating transport infrastructure projects that aim to enhance **system-wide resilience**, however it should be noted that MCA is not recommended by HMT Green Book (which instead favours MCDA with swing weighting). A process chart illustrating these steps are shown below.

Detailed aspects of CBA – Risk Appraisal and Wider Uncertainty Techniques

The significant **risks and uncertainties** associated with assessing resilience means that additional emphasis is likely to be required on the risk and uncertainty analysis in shaping the Value for Money assessment. Risk and uncertainty techniques are an aspect of, or enhancement to, CBA rather than an alternative to CBA itself.

Whilst strictly CBA should reflect an expected value of outcomes across all possible scenarios, it most often focuses on comparing the monetised benefits and costs of a project under a single, expected future scenario. However, resilience appraisal requires consideration of uncertainty and variability over the long-term. **Assessing appraisal outcomes across a range of potential scenarios** where outcomes are highly divergent could help to address some of this uncertainty.

NIC’s 2022 Managing Uncertainty report highlights the importance of exploring how multiple scenarios may influence a transport scheme’s performance. **Scenario planning** involves the development and analysis of alternative futures. By modelling outcomes under different conditions, decision-makers can assess how various interventions perform when the system is exposed to significant stressors or unexpected occurrences. The use of **multiple emissions scenarios** can help to manage some of the uncertainty within climate projections (DfT, 2024f). Highways England and Network Rail employ **scenario analyses** to test how investments may help the system withstand closures from floods or multiple asset failures. Further examples are provided in.

Risk appraisal is often undertaken within CBA in TAG appraisal using a **Quantified Risk Analysis (QRA)**, with specific adjustments made to scheme costs to reflect identified risks.

Sensitivity analysis is a technique used to explore how changes in key assumptions or inputs affect the outcomes of an appraisal. It helps test the robustness of decisions by showing how rankings or outcomes might shift under alternative conditions. Sensitivity analysis is consistent with the National Highways Appraisal Manual approach which recommends estimating the 97.5th percentile of incident durations – essentially a ‘close to worst-case’ scenario for how long disruptions might last.

The National Infrastructure Commission (*Anticipate, React, Recover: Resilient infrastructure systems*, 2020) explicitly advocate for the use of **regular stress tests** for infrastructure systems, encouraging planners to actively check for vulnerabilities and assess how proposed measures hold up under worst-case or multi-risk scenarios. Taking a broader ‘total value systems’ approach to stress-tests involves integrated analysis of value, systems, shocks/stresses, vulnerability measurement and prioritisation. This encourages understanding of the broad purpose and scope of a system, rather than a component-centric siloed view (Field and Look, 2018).

Other innovative methods have been developed to formally incorporate risk into transport appraisal. For example, Lin et al. (2024) propose a **risk-resilience optimisation framework** that incorporates uncertainty into restoration planning for transport infrastructure. Their model uses **Conditional Value at Risk with Regret (CVaR-R)** to account for worst-case scenarios, linking probabilistic risk measures with resilience outcomes such as travel time and network functionality.

As described in Section 2.3.1, uncertainty is distinct from risk in that there may be insufficient information to assign probabilities to potential outcomes. *The Economic Analysis of Climate Adaptation* report by DEFRA (2016) highlights a range of decision-making under uncertainty appraisal techniques to better capture uncertainty and presents a selection of these techniques, their advantages and how uncertainty is captured.

Table 12. Potential uncertainty appraisal techniques for climate resilient appraisal. Source: Defra analysis of Economics of Climate Change Adaptation in Europe Toolbox (2016).

Appraisal method	Suitable appraisal context	How manages uncertainty
Real options analysis	Ideal for evaluating large capital investments over the medium-term where climate risk probabilities are available and future operational changes are possible.	Explicitly addresses uncertainty by analysing option performance across various potential futures.
Robust decision-making	Best for long-term investments where sizeable uncertainties exist and both quantitative and qualitative information need to be considered.	Explicitly addresses uncertainty by using a maximum-minimum approach to assess options under diverse climate scenarios (identifying the maximum outcome as the most favourable scenario and the minimum outcome as the least favourable).
Iterative risk management	Suitable for policy appraisal over the medium- to long-term when clear risk thresholds are identified.	Explicitly addresses uncertainty by promoting iterative analysis, monitoring, evaluation and learning.
Portfolio analysis	Effective when multiple complementary adaptation actions are possible and good economic and climate data are available.	Explicitly addresses uncertainty by examining the complementarity of adaptation options for future climates.

Real option analysis is a decision-making framework that evaluates investment choices under uncertainty and evolving risks providing flexibility to adapt as conditions change. Unlike CBA which assumes a fixed investment path, ROA acknowledges that decisions can be adapted as new information becomes available and uncertainties unfold. It was used to appraise flexible pathways for upgrading the Thames Barrier and associated flood defences. Rather than committing to a single large investment, the plan allows for staged interventions based on observed sea level rise, preserving adaptability over time.

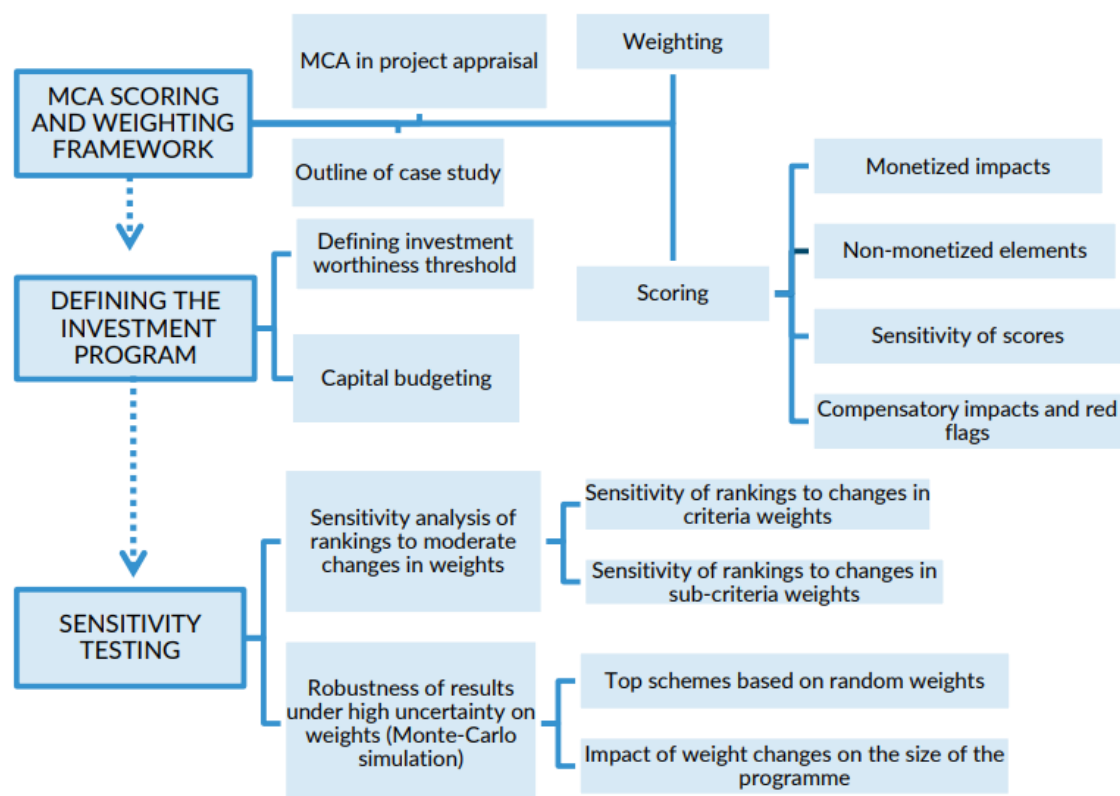
Iterative risk management is a cyclical process of continually identifying, assessing, and mitigating risks, which enables adaptive responses to emerging threats. For example, through the use of the enterprise risk management (ERM) framework within TfL which manages all risks including climate risks to its transport network (TfL, 2023).

Portfolio analysis assesses the risks and returns of multiple transport assets or projects together, enabling more resilient decision-making by diversifying investments and prioritising those that strengthen overall network robustness. NIC's *Surface Water Future Risk and Investment Needs* paper (2022) tests fifteen different flood adaptation strategies using a tool called FFE. These strategies were grouped into three types: ones that focuses mainly on surface solutions like green infrastructure (SuDS), ones that relies more on underground drainage systems, and the third being a mix of both. Each strategy was adjusted to fit local conditions, like urban or rural settings. The tool then calculated how much each option would cost and how well it would reduce flood risk, helping decision-makers choose the best portfolio of options based on budget and impact.

Robust decision making (RDM) involves systematically evaluating options under wide-ranging uncertainties to identify strategies that remain effective across many future scenarios, thereby supporting resilient transport appraisal. This is consistent with the 'total value systems' approach described above.

In addition to these uncertainty methods, where risk probabilities cannot be broadly agreed through expert judgement or supplementary analysis, PA Consulting (2024d) recommended that **'probability switching values'** should be calculated. These values can convey important information to decision-makers on risk, even with a complete absence of any robust risk information. For example, a situation might be encountered where the appraisal has identified risks to be addressed, has calculated the costs of the intervention, and has estimated the potential losses associated with the risk manifesting, but reliable information on the likelihood of the risk occurring cannot be obtained. In this situation, switching values can be deployed as a 'break-even parameter value' in the appraisal using an 'expected value' framework. The probability of the risk that the decision-maker would need to believe in order for the intervention to represent a minimum desired level of Value for Money can be calculated. This allows decision-makers to use informed judgement whether to progress the intervention, making appropriate trade-offs between risks to economic resilience and other risks in their portfolio.

Figure 13. Development of MCA scoring and weighting framework including CBA elements. Source: CEDR adapted from Gühnemann, Laird, & Pearman (2012)



Key Findings

- **Cost Benefit Analysis (CBA)** faces significant challenges in fully capturing the long-term, uncertain, and often non-monetised benefits of resilience interventions in transport.
- **Scenario-based appraisal** is increasingly recognised as essential for accounting for resilience, with methods such as scenario analysis, regret analysis, breakeven analysis, and stress testing enabling decision-makers to appraise performance across a range of plausible futures and support more robust investment decisions under uncertainty.
- **Resilience standards and cost-effectiveness analysis** offer alternative value-for-money frames that shift decision-making from monetising every benefit to meeting predefined service or resilience thresholds. These approaches help prioritise investments by focusing on whether options meet agreed resilience targets, rather than their expected NPSV.
- **Setting appropriate resilience standards** is methodologically complex and dependent on clear risk appetite, societal values, and practical feasibility. The absence of defined standards in many contexts limits the universal application of cost-effectiveness approaches.
- Broader appraisal toolkits are gaining traction, with hybrid frameworks combining CBA, Scenarios and Multi-Criteria Analysis (MCA) to capture qualitative impacts, equity trade-offs, and stakeholder priorities. These approaches might support more holistic decision-making.
- **Advanced risk and uncertainty techniques**, including Real Options Analysis, Robust Decision-Making (RDM), Iterative Risk Management, and Portfolio Analysis, allow decision makers to address deep uncertainty and adapt investment strategies over time. These methods support flexibility, staged intervention, and continual learning, reflecting the evolving nature of climate and systemic risks.
- Case studies such as the Resilience and Disaster Recovery (RDR) Tool in the US and the Exeter to Newton Abbot Geo-Environmental Resilience Study in the UK demonstrate successful integration of **hybrid appraisal approaches** for long-term infrastructure resilience.

- **Persistent appraisal gaps** mean further advancement in uncertainty frameworks and the integration of resilience metrics into appraisal is needed.

3.5 Resilience in Value-for-Money and Investment Decision-Making

This section explores the role that resilience appraisal plays in shaping VfM conclusions and examines the interfaces between a TAG economic appraisal of resilience and the strategic assessment of resilience outside the TAG framework. In this section we seek to address the following research question:

Key research question: *How is resilience being considered in reaching value-for-money conclusions and factored into decision-making on transport investment?*

3.5.1 Resilience in the TAG framework

In addition to established benefit categories, there may be a case for capturing resilience as a new benefit category within the CBA. This could either be as a monetised benefit (for example, through quantifying avoided losses such as those calculated as part of the National Highways Appraisal Manual for severe incidents) or as a non-monetised benefit category. The DfT's updated (2025i) 'Value for Money Framework' supports this approach by encouraging the inclusion of non-monetised assessments, recognising that long-term societal and environmental benefits are not always easily captured in monetary terms.

Whilst attractive, incorporating resilience into the TAG appraisal framework as a distinct impact also raises a number of appraisal challenges and complications, some of which this review has identified:

- **Different methods** for assessing resilience can **produce very different cost and benefit estimates**, making it hard to compare projects on a like-for-like basis.
- **Risks may be fluid and fast-moving.** Following a shock, the transport system may not return to a previous state, meaning the baseline for the appraisal may shift dynamically over time.
- **Diverse, wide-ranging and long-lasting nature of risks** to the transport system, meaning the pathways to model impacts may be diverse and uncertain, spanning economic, environmental and social dimensions.
- **Impacts may be complex and inter-related** (such as resilience, reliability and option-value), making them difficult to clearly disentangle the impacts and identify any additional sources of value.
- **Additional trip-making** – major enhancements of the network can lead to additional trip-making that may counteract the benefits to resilience that may have otherwise been felt by analysing existing trips only.

In this context of these challenges, it should be considered whether capturing resilience within the **risk or uncertainty appraisal** within the economic appraisal, supplementing the CBA is a more appropriate route for capturing resilience impacts. This will be explored in more detail in the Conceptual Framework.

3.5.2 Accounting for Resilience Through the Discount Rate

A fundamental alternative for incorporating resilience considerations into economic appraisal across all transport projects is through **adjusting the discount rate**. Discounting is a critical methodological aspect in the appraisal of transport resilience, reflecting how future benefits and costs are valued relative to present impacts. In the UK, the Green Book sets out the standard approach, applying a Social Time Preference Rate (STPR) of 3.5% for the first 30 years, then applies a declining discount rate beyond 30 years (and again beyond 75 years) to reflect uncertainty over long horizons. Any further adjustment to account for resilience would therefore need to consider these existing reductions to avoid overcompensation. This technique is grounded in the principle that people generally prefer benefits now rather than later. However, this approach presents challenges for resilience appraisal, particularly for projects designed to yield benefits far into the future, such as climate adaptation or infrastructure upgrades.

One key issue is whether appraisal should apply each individual's personal discount rate (PDR) or to impose a single STPR. A PDR is consistent with revealed preferences and reflects actual behavioural trade-offs, however this can be impractical to estimate for everyone affected by the investment and decisions affect multiple generations where PDRs are not possible to ascertain. The Green Book takes the normative approach of recommending an STPR in line with social welfare maximisation.

These concerns are compounded when resilience benefits are uncertain or intergenerational in nature. Alternative approaches that may better capture the value of resilience under uncertainty. One such approach is the Consumption Capital Asset Pricing Model (CCAPM), which adjusts discount rates based on consumption risk. Unlike the traditional CAPM, which links asset returns to market performance, CCAPM uses a consumption beta to measure how sensitive an asset's returns are to changes in aggregate consumption. In public investment appraisal, this allows discount rates to reflect how a project's benefits co-move with consumption, which lowers the rate for investments that hedge against consumption shocks, such as infrastructure that remains operational during crises.

Another proposed alternative is the use of certainty equivalents, which adjust expected values to reflect societal risk aversion before applying a standard discount rate. Rather than modifying the discount rate itself, this approach transforms the valuation of uncertain outcomes, capturing the insurance-like value of resilience, especially in the face of low-probability, high-impact events. This is sometimes referred to as the option price, particularly when the benefit is framed as the value of having the option to avoid or mitigate future adverse events. Compared to CCAPM, the certainty equivalent method offers a more transparent separation between time preference and risk valuation and may be especially useful when resilience benefits are difficult to monetise or when stakeholder risk preferences vary.

Both approaches offer potential improvements over the Green Book current treatment of risk. This is explored in a detailed review of social discounting by Freeman, Groom and Spackman (2018), commissioned by HM Treasury, which examines the limitations of the Green Book framework and advocates for more theoretically grounded methods of incorporating risk. The report critiques the inclusion of a 1% adjustment term for risk, noting that it serves as a catch-all for various forms of uncertainty, including catastrophic societal collapse, systematic underestimation of project risks, and macroeconomic volatility. While this 1% adjustment is pragmatic, Freeman et al. argue that such risks are conceptually distinct and may be better addressed through project-specific benefit valuations or explicit risk premia, rather than being bundled into a single discount rate component. Catastrophic societal collapse refers to low-probability, high-impact events such as major wars, pandemics or technological disruptions that could eliminate or radically alter the returns from all projects. Systematic underestimation of project risks reflects the persistent optimism bias and unforeseen technical failures observed in major infrastructure programmes. Macroeconomic volatility captures uncertainty in long-run consumption growth, which interacts with discounting through precautionary savings motives and underpins arguments for a declining term structure of rates, particularly relevant for resilience investments with benefits far into the future.

The report's analysis shows that incorporating consumption volatility and precautionary savings motives would theoretically lower the discount rate, especially for projects with long-term or intergenerational benefits. They also explore the use of CCAPM to account for systematic project risk, suggesting that projects with counter-cyclical benefits, such as resilient infrastructure (which can deliver higher marginal utility in low-consumption states), may warrant lower discount rates. These findings reinforce the need for a more nuanced approach to discounting in resilience appraisal, one that reflects both ethical considerations and the economic characteristics of risk.

Building on this, the Green Book Review (2025) has acknowledged similar concerns and announced an independent review of the STPR to ensure that long-term transformational projects are not undervalued. The review will examine whether the current discount rate components, including pure time preference, expected consumption growth, and the risk adjustment, remain appropriate in light of uncertainty and systemic shocks. HM Treasury has indicated that this review will consider whether the current approach undervalues long-term benefits and will draw on international practice where risk premia and declining term structures are used to reflect uncertainty over time (HM Treasury, 2025).

Illustrative Example: Adjusting Discount Rates for Resilience in Transport Appraisal

Consider a hypothetical rail resilience project: upgrading drainage and earthworks along a flood-prone corridor to reduce the likelihood of prolonged closures. Under standard Green Book discounting (3.5%

STPR for 0-30 years), benefits from avoided disruption are heavily discounted, reducing their influence on the Benefit-Cost Ratio (BCR).

If resilience benefits are treated as counter-cyclical, a lower discount rate could be justified using a Consumption Capital Asset Pricing Model (CCAPM) approach. For example:

Base case (0-30 years): STPR = 3.50%, NPV of benefits = £120m, BCR = 1.40

Adjusted for resilience (0-30 years): STPR = 3.25%, NPV of benefits = £130m, BCR = 1.52

This adjustment reflects the insurance-like value of resilience and its long-term societal benefits. While this is a stylised example, it demonstrates how discounting assumptions can materially affect VfM conclusions for projects with benefits accruing far into the future.

3.5.3 Interaction Between the Strategic and Economic Assessments

In understanding how decision-makers weigh resilience considerations, it is important to understand the role that the **economic appraisal plays alongside the strategic assessment** in decision-making.

Stakeholders across the transport system have different objectives they find most important (OECD/ITF, 2024). In decision making, public bodies involved in the allocation of resources into the transport system, such as DfT, National Highways and Network Rail, ultimately shape the **'choice architecture' that governs the role that the economic appraisal** can play. Through their strategies and policies related to resilience (see Section 2.2), these bodies oversee governance structures that apportion responsibilities for resilience (amongst other objectives) across this ecosystem.

For the example of roads, the DfT shapes overall policy for the resilience in the transport system, National Highways may have oversight of its application to the Strategic Road Network (SRN) and the scope of the interventions to deliver resilience may then be further spread over different operating divisions (i.e. technology, operations and enhancement portfolios), and different programme and projects within this. A Senior Responsible Owner (SRO) charged with overseeing an economic appraisal of different route options for a specific regional road enhancement project, may have a constrained remit for resilient options, and is unlikely to have access to the **full range of resilient interventions across the resilience life-cycle** set out in Section 2.1.

In other words, the VfM assessment of interventions that deliver resilience is contingent on the broader organisational context and its remit in resilience policy and strategy. Project identification should reflect, or respond to, the changing objectives of transport policy (ITF, 2022). This introduces an important question for the economic appraisal – should this seek to measure the specific resilience of the asset or infrastructure in question or seek to measure the asset or infrastructure's contribution to system-wide resilience. The concept of route resilience is most consistent with the former, and network resilience most consistent with the latter.

This also raises the possible opportunities that could be realised through greater use of **programmatic and portfolio-level appraisal** that correspond to programme and portfolio level resilient objectives. These forms of economic appraisal are potentially more likely able to weigh the full range of resilience options against each other and to accurately analyse the system-wide inter-dependencies and cascading factors that exist. Resilient interventions that do not represent Value for Money when examined individually within a dozen different road schemes in a region, **may represent Value for Money when analysed as a regional programme of investment** – due to the interdependencies and potential for cascading failures within the regional transport system.

Therefore, this emphasises the important role the strategic assessment can play in setting out the choice architecture at play, the allocation of responsibilities for resilience and how this shapes the appropriate scope and role of the appraisal. In doing so, the strategic assessment may need to clearly articulate which aspects of the resilience cycle are within the remit of the economic appraisal. For example, a scheme targeting flood-prone infrastructure may appraise mitigation and recovery options only, while a digital transport system may appraise response and learning options (e.g. from cyber threats).

PA Consulting's (2025) supplementary Green Book guidance on appraising economic resilience also emphasises that the economic appraisal is framed by whether resilience is the **primary objective of the intervention, a secondary or supporting objective, or a consequential impact rather than an explicit goal.**

Key Findings

- There's a growing case for including resilience in **cost-benefit analysis (CBA)**, either as a monetised or non-monetised benefit, supported by the DfT's 2025 Value for Money Framework.
- Incorporating resilience into the **TAG framework is complex** due to varied assessment methods, shifting baselines post-shock, diverse risk types, and overlapping impacts like reliability and additional trip-making.
- Given these challenges, **risk or uncertainty appraisal** should play a greater role in shaping Value for Money conclusions. Arguably, CBA frameworks underpinned by literature such as Zhang et al (2023) combined with enhanced risk and uncertainty techniques such as probability switching values show the greatest promise as practical tools for appraisal. This is taken forward further in the conceptual framework in Section 4.
- A fundamental alternative is **adjusting the discount rate** to reflect resilience considerations. The current UK approach to discounting (STPR) may undervalue long-term resilience benefits, especially due to issues like double discounting and intergenerational uncertainty.
- The Green Book Review (2025) acknowledges these concerns and is **reviewing the STPR** to better reflect long-term, transformational project benefits.
- The role of economic appraisal in assessing resilience is shaped **by broader organisational strategies and governance structures**, which influence what resilience options are considered and who is responsible for them.
- Appraising resilience at the **programme or portfolio level** may better capture system-wide benefits and interdependencies than project-level assessments, which can miss the value of interventions when viewed in isolation.
- Economic appraisal should reflect whether resilience is a **primary, secondary, or incidental objective**, and align with the specific stages of the resilience lifecycle relevant to the intervention.

4 Conceptual Framework for Appraising Resilience in a Transport Context

This chapter sets out an initial conceptual framework for appraising resilience in a transport context. It draws together and builds on the key insights from the literature review to:

- Articulate the importance of capturing resilience impacts in transport appraisal and the need for a coherent framework.
- Define resilience in a transport context and explain the relationship between resilience impacts and existing TAG categories.
- Articulate the CBA Expected Value frame of reference that has been chosen and the possible alternative approaches.
- Propose specific approaches for strategic, economic and risk and uncertainty assessment (both monetised and non-monetised forms of assessment).
- Highlight outstanding appraisal challenges and recommended priorities for further research,

This chapter seeks to provide a clear, proportionate basis for incorporating resilience appraisal into TAG – with specific recommendations articulated in Chapter 5. **Chapters 4 and 5 have been developed to be read together on a standalone basis – relevant material from Chapters 2 and 3 has therefore been summarised and included where this context is required.**

4.1 The Importance of Addressing Resilience in Appraisal

4.1.1 The Risk Landscape for Transport

Resilience refers to the “*ability to absorb and adapt in a changing environment*” (ISO, 2021). In an increasingly volatile global landscape, the resilience of transport systems has become a strategic priority for safeguarding connectivity, economic activity, environmental sustainability and social wellbeing.

The UK transport system faces an **increasingly complex risk landscape** characterised by the interplay between hazards (e.g. extreme weather, cyberattacks), exposure (assets, people in harm’s way), and vulnerability (susceptibility of systems to damage) (Cabinet Office, 2023). The risks to the UK transport system are both acute and chronic in nature (Cabinet Office, 2023a).

Acute risks are discrete, high-impact events that typically require an immediate response. They include severe weather incidents (storms, flooding, snow), cyber-attacks, pandemics, major accidents, and malicious acts such as terrorism or sabotage. These events can cause sudden and widespread disruption, often overwhelming transport network capacity and triggering cascading failures across interconnected systems. Recent examples include the 2023 and 2025 National Air Traffic Services (NATS) technical outage, the Stonehaven rail derailment, or the Covid-19 pandemic.

Chronic risks are persistent, long-term stressors that exert sustained pressure on transport systems, erode system stability gradually and can amplify the frequency and severity of acute incidents. Examples include rising temperatures and sea levels, ageing infrastructure, demographic shifts, workforce rigidities, and growing dependency on digital technologies. Real-world events include the UK lorry driver shortage, and the structural deterioration of the Hammersmith Bridge eventually leading to closures.

Acute and chronic risks are **deeply interconnected**: chronic stressors like ageing infrastructure or workforce shortages often increase vulnerability and diminish response capacity during acute shocks, while recurring acute disruptions expose systemic weaknesses and reshape longer-term trends. This risk landscape is also **changing rapidly**, with climate-driven weather extremes, greater cyber and geopolitical threats, and rising digital dependence all likely to be increasing the materiality, complexity, and frequency of shocks (Cabinet Office, 2025a).

4.1.2 Policy Evolution and Appraisal Gaps

The Government Resilience Framework (Cabinet Office, 2023a) committed to taking several actions for strengthening the UK resilience system. The 2025 UK Government Resilience Action Plan (Cabinet Office, 2025a) highlights the importance of strengthening the resilience of the UK’s transport systems as part of its focus on Critical National Infrastructure (CNI), recognising its central role in supporting the economy and responding to emergencies.

DfT and its delivery bodies have introduced measures to embed resilience into planning and operations, in line with the Department's 'Fit for a changing climate?' (2024a) report principles. Mode-specific initiatives include Network Rail's Weather Resilience and Climate Change Adaptation Plan (Network Rail, 2023) and National Highways' Climate Change and Strategic Road Network (2024b) initiatives.

Resilience impacts are therefore becoming an increasingly important consideration to decision making of transport schemes. Although exploratory analysis of resilience impacts has been conducted in specific transport contexts (such as the National Highways Appraisal Manual), there is still no generally accepted approach for the economic appraisal of resilience impacts of transport investment schemes in DfT Transport Analysis Guidance (TAG).

4.1.3 Introduction to this Conceptual Framework

The overall aim for this conceptual framework is to propose a robust, defensible basis for appraising resilience within TAG. It covers:

- Proposed definitions of resilience and thresholds for incidents that would be captured by the appraisal
- The core economic principles underpinning the appraisal, the key challenges this presents and the potential VfM frameworks that should be adopted
- The avoidance of double counting impacts, considering the potential overlap between resilience impacts and existing TAG appraisal categories (such as reliability, and option value)
- The key analytical approaches for appraising resilience in a transport context – covering strategic, economic and risk and uncertainty dimensions.
- Outstanding considerations, including any evidence gaps and future research priorities.

The conceptual framework has been based on a literature review of approaches to resilience appraisal, conducted using a rapid evidence review methodology, adapted from the principles of the Rapid Evidence Assessment (Collins et al., 2015). This has included reviewing over 200 sources of published literature and other non-published evidence, covering academic literature, government reports and grey literature in both the UK and globally.

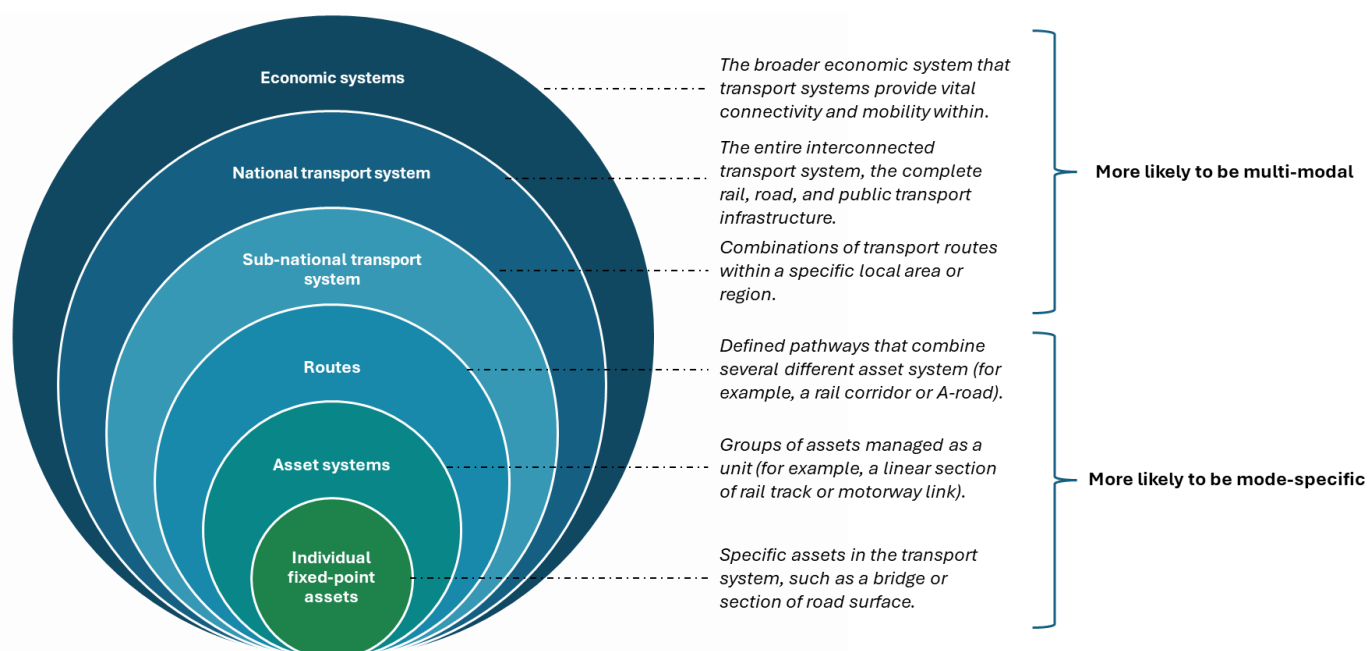
4.2 Defining Resilience for TAG Appraisal

4.2.1 Broad Definition of Resilience in a Transport Context

Resilience in the context of a transport system can be defined as '***The ability of the transport system to anticipate, withstand, recover from, adapt and learn from a wide range of shocks and stresses to support connectivity, economic activity, environmental sustainability and social wellbeing***' (PA Consulting, 2025). While alternative definitions exist, modern frameworks emphasise the role of forward-looking adaptation (National Infrastructure Commission, 2024). Resilience in a transport context means not only bouncing back after disruption, but also having **adaptive capacity** – the ability of transport systems to adjust and improve in response to changing risks and threats (Field et al., 2017).

The resilience of the transport system **builds cumulatively** across several layers (see Figure 14, below), from individual fixed-point assets through networks and economic systems, with weaknesses at lower levels cascading upward and strong policy and planning at higher levels providing system-wide support.

Figure 14. The layers of resilience in transport systems. Source: PA Consulting analysis incorporating applied learnings from Field and Look (2018), Kazima et al. (2023) and Begantino et al. (2024).



This framework also provides the foundation for understanding differences between ‘route’ and ‘network’ resilience (National Highways, 2022a). **Route resilience** refers to the ability of an individual route to cope with a major incident, whilst **network resilience** refers to the extra capability that the route gives to the wider network to cope with the incident.

Resilience is closely related but distinct to reliability, robustness, recovery, and redundancy. **Reliability** refers to consistent performance under normal operating conditions, such as predictable journey times (Department for Transport, 2025b) – see Section 4.2.2 below. **Robustness** is the ability to resist degradation when exposed to stress (Ge, L., Voß, S., and Xie, L., 2022). **Recovery** describes the speed and effectiveness with which a system returns to its original state following disruption (Cabinet Office, 2013). **Redundancy** refers to the availability of alternative routes or resources that allow continued operation when part of the system fails (Gerges et al., 2022).

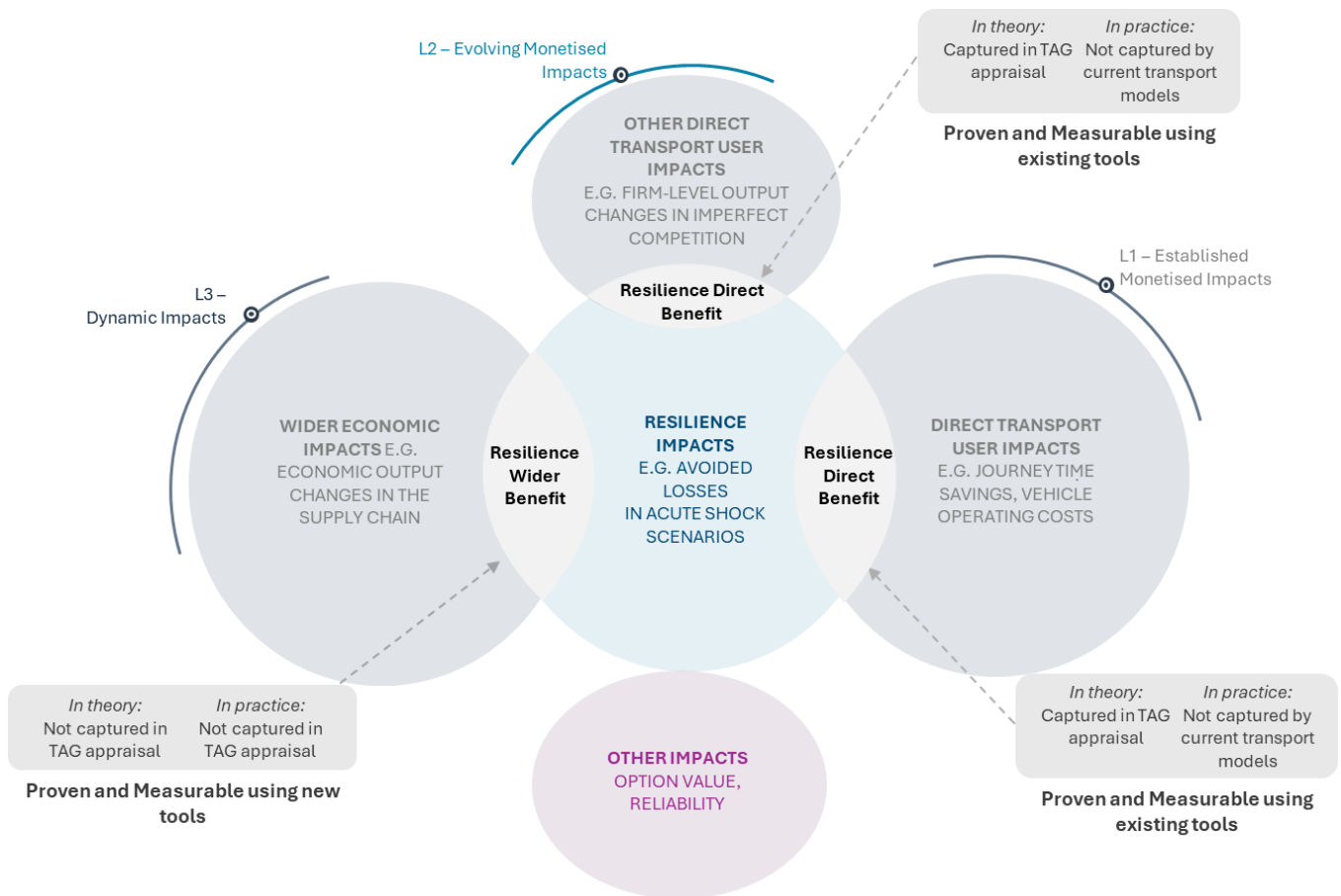
4.2.2 Resilience Impacts and Interfaces with TAG Impact Categories

Transport networks support connectivity for transport users, facilitate employment opportunities, boost productivity and investment and provide access to essential services (DfT, 2025a). The literature consistently demonstrates that **transport disruptions can lead to significant impacts** – both to users of the transport system and the economic activity the transport system helps to support. It can lead to other societal consequences such as reduced access to essential services (ITF, 2022). In the long term, it is feasible that persistent transport disruptions impacting a particular area could impact long-term decision-making of transport users or other economic agents (Larcom et al., 2017).

Avoiding these losses through additional resilience therefore **represents an increase in social welfare** in a welfare-based appraisal framework which is the basis for TAG (see Section 4.4.2 below). It is important to consider how this broad understanding of resilience impacts, aligns with, complements, or potentially overlaps with existing TAG impact categories. This ensures that the resilience appraisal captures additional impacts only and avoids double-counting. A mapping of existing selected TAG impact categories is presented in Figure 15.⁹

⁹ In line with the Four Questions Resilience Framework presented in Section 4.4.1, this maps resilience “for whom”. A selection of the most relevant TAG impact categories has been identified from the literature review. Resilience impacts may cover broader areas not listed here – for example safety impacts, environmental impacts or social impacts – however, these are not expected to be material to most appraisals.

Figure 15. Distinguishing resilience from other TAG impact categories



In summary, this analysis finds that:

- In theory, transport appraisal would capture all potential **transport user benefits** (journey time savings etc) that additional infrastructure or resilience improvements bring. However, in practice, transport models are typically calibrated based on normal operating conditions and do not take account of long duration incidents that disrupt traffic flows.
- Major incidents also lead to an increase in business and freight user costs, reduced output and increased prices in the presence of imperfect competition. This leads to further welfare losses in line with the existing TAG impact, **output change in imperfectly competitive markets (OCICM)**. Given this impact is estimated from changes to business user journey time savings derived from transport models, they also would not take account of acute risks.
- For the supply chain dependent on businesses, freight or workers using the transport system, the unanticipated and short-run disruption means that the current use of capital and labour is suddenly made idle and these inputs are not redeployed in alternative ways. This results in a **loss of value-added in the supply chain and wider economy** which is not presently captured in TAG appraisal. Further reductions in GDP through consumption and earnings channels could also be feasible.
- **Reliability** refers to the variation in journey times that individuals are unable to predict, encompassing day-to-day variability from recurring congestion and non-recurring disruptions. Major incidents could, in theory, influence user predictions around network variability from non-recurring disruptions. However, in practice, **pragmatic boundaries exist to distinguish reliability and resilience** (see Section 4.2.3 below).
- Similarly, **option value** is a related but distinct impact category to resilience. While resilience reflects the ability of the transport network to withstand and recover from disruption affecting known or expected journeys, option value captures the societal benefit of maintaining redundancy for unknown or latent demand (i.e. the benefit individuals gain from having access to alternative modes, routes, or services, even if they do not use them regularly).

4.2.3 Definition of Resilience for TAG Appraisal

TAG appraisal of resilience impacts requires **an interpretation of the definition set out in Section 4.2.1 that is measurable and can be pragmatically deployed in scheme assessment**. When considering acute risks that impact transport systems, the severity of an incident is considered a pragmatic approach to determine which incidents are within the scope of resilience appraisal, taking care to avoid double counting impacts.¹⁰ The **duration of an incident** (impact in delay minutes to return to normal operating conditions) is likely to be the most practical cross-modal measure (Gonçalves et al, 2024), but volumetric-based measures (such as the number of transport users impacted) could also be used. The application of threshold measures across different appraisal contexts and transport modes is described below.

Threshold measures for resilience in transport

There are no universally accepted threshold measures for acute shock events in transport. However, some mode-specific thresholds have been developed. For example, Rail Delivery Group (2024) categorises three broad types of emergency: **Level 1 – Significant** (wide focus that requires central government engagement), **Level 2 – Serious** (wide and prolonged impact that requires central government coordination) and **Level 3 – Catastrophic** (exceptionally high and widespread impact requiring immediate central government intervention).

Whilst RDG defines these thresholds qualitatively, **quantitative measures** are likely to be required for transport appraisal. Engagement with rail industry bodies has identified the following **active network thresholds** being considered: impact in delay costs, response times, recovery handback times, recovery times. Other potential measures might include: average time to recover, service availability, customer impact index, time to restore critical links and recovery capacity.

Other dimensions of a shock may influence its severity alongside these factors – for example mortality impacts or impacts on specific critical infrastructure, supply chains or essential services. It is also important to recognise that the relevant thresholds for resilience can vary depending on the specific appraisal context – for example, whether a local, regional or national scheme is being appraised. For a national scheme, a shorter duration threshold than a local scheme may be appropriate if the incident impacts a larger number of transport users. Itani and Shalaby (2021) demonstrated how incident duration and the number of people affected are key determinants impacting user delay costs when analysing subway outages in Toronto.

National Highways distinguishes reliability from resilience based on the duration of a disruption. In appraisals using the MyRIAD tool, disruptions lasting less than six hours are classified as reliability issues, while those exceeding six hours are treated as resilience impacts (National Highways, 2022b).¹¹ This threshold is drawn from MyRIAD guidance and software, which constrains the build-up of long-duration incidents by limiting the maximum incident duration to 6 hours and maximum link utilisation to 0.95. **Incidents lasting more than six hours can trigger significant behavioural responses** such as rerouting or trip cancellation, and therefore should be classified as incidents impacting resilience (National Highways, 2023).¹²

From an operational perspective, DfT's risk practitioners generally use a four-hour cut-off point for treating an incident as an emergency. This is based on a humanitarian perspective when transport users become vulnerable and additional welfare support is required (for example, enacting driver welfare plans for road users with young children). In addition, Cabinet Office Risk Identification Guidance (HM Government, 2025) applies four thresholds to determine a risks inclusion in the National Security Risk Assessment (NSRA)¹³.

Data-driven analysis of actual incident lengths and their impact on the road network can also serve to refine the appropriate incident duration for resilience appraisal. Below, a case study example of

¹⁰ Given their long-term systemic nature, chronic risks cannot be measured by incident durations and require an alternative appraisal approach.

¹¹ See Economic Appraisal Report (EAR) for the Lower Thames Crossing DCO.

¹² Wider literature supports the finding that major incidents trigger significant behavioural responses. Larcom et al. (2017) found that 48 hour strikes on the London Underground in February 2014, led to many commuters changing their travel routes after being forced to experiment with alternatives. This behavioural shift persisted long after normal underground services resumed.

¹³ Risks must: qualify as civil emergencies, exceed minimum likelihood requirements (at least a 1 in 100,000 probability of occurring in the next year), exceed minimum impact threshold (causing considerable harm) and represent plausible scenarios.

incident durations on the Dartford Crossing in 2014 is examined. This highlights while incidents exceeding six hours are rare, their impact can be disproportionately large. The most disruptive incidents, such as the protester action in 2022 which closed the crossing for 37 hours, resulted in the largest impact.

Whilst conclusive evidence on relevant incident lengths would require detailed transport modelling across multiple-modes, the **six-hour cut-off is considered to provide a pragmatic boundary** to separate day-to-day variations in travel times from more severe disruptions, helping to avoid double-counting benefits with existing reliability measures. A longer cut-off of six hours over alternatives such as four hours also helps to focus analytical effort on the most severe incidents. However, the use of any fixed duration may oversimplify the complex nature of disruption impacts, particularly when user costs are driven not only by duration but also by the number and type of users present. Further quantitative research on the impact of incidents, for example leveraging DfT's digital twin, would be required to illuminate these differences and to recommend varying thresholds across appraisal contexts and transport modes.

4.3 The Value for Money Frame of Reference

4.3.1 Strategic, Economic and Risk & Uncertainty Assessments

The literature has highlighted three different dimensions that should be considered to fully assess resilience in a transport context – strategic dimension, economic appraisal and risk and uncertainty assessment. The conceptual framework focusses on economic assessment whilst recognising key linkages with other assessment types:

Table 13. Forms of resilience assessment

Assessment	Description	Tools	Example
Strategic dimension (Strategic Case)	Strategic resilience needs and operational performance assessment of transport systems	KPI/KRI dashboards, ranked risk scores, resilience maturity frameworks, forecasting	<i>Rail Resilience Project, Rail Delivery Group (2021) measures individual and organisational capabilities using KPIs and KRIs, with regular maturity assessments.</i> <i>Climate Change Adaptation Plan, TfL (2023) integrates climate risk into strategic planning through forecasting.</i>
Economic appraisal (Economic Case)	Assessment of losses from major incidents incorporated in Benefit Cost Ratios or wider Social Cost Benefit Analysis (CBA)	Monetised assessment (welfare or supplementary GVA lenses); Non-monetised assessment (qualitative scoring, MCA)	<i>Rotterdam Port Adaptation Strategy used CBA to quantify both direct and indirect benefits over a multi-decade horizon.</i> <i>Lower Thames Crossing Economic Appraisal Report (National Highways, 2022b) appraises resilience impacts qualitatively.</i>
Risk and uncertainty assessment (Strategic / Economic Case)	Quantitative or qualitative assessment of alternative loss outcomes, often based on probabilities or probability distributions	Stress-testing, simulation modelling, probability switching values, adaptive pathways	<i>The Thames Estuary 2100 project applied a standardised NPSV analysis with an adaptive pathways approach as part of a comprehensive reassessment of costs and benefits incorporating climate projections under various sea-level rise scenarios. (Environment Agency, 2023; JBA Consulting, 2024).</i>

The strategic dimension plays a key role in defining the scope of the economic appraisal through identifying the strategic objectives and any resilience needs, establishing the relevant resilience standards, setting out potential resilience strategies, highlighting the extent to which resilience impacts

are relevant and proposing any ways in which it should be measured. This strategic framework is explained in Section 4.4.1.

In this strategic context, **economic appraisal** is undertaken. The literature indicates a wide range of available appraisal frameworks for appraising resilience. However, the central and most robust approach is based on an expected value framework for calculating avoided losses in Social Cost Benefit Analysis (CBA), explained in Section 4.4.2. Extensions of CBA or alternatives to CBA are defined as complementary or alternative appraisal frameworks for consideration in specific circumstances in Section 4.3.3.

The significant risks and uncertainties associated with appraising resilience means additional emphasis should be placed on **risk and uncertainty assessment**. This should inform the VfM conclusion made in the economic appraisal – the risk and uncertainty framework is explained in Section 4.4.4.

Whilst this framework can apply to both acute and chronic risks, there is more evidence in the literature relating to the former. It is therefore considered proportional to elaborate the framework with specific reference to **acute risks**; whilst considering specific appraisal considerations for **chronic risks** separately (see Section 4.4.5).

4.3.2 Economic Assessment – Expected Value Framework

When **risk probabilities can be robustly estimated**, there is the potential to include avoided loss impacts in Net Present Social Value (NPSV) analysis through an expected value framework: potential loss multiplied by the likelihood of the risk materialising. This relationship is captured in the risk equation (DfT, 2025c):

$$\text{EXPECTED VALUE OF LOSS} = \text{LIKELIHOOD} \times \text{LOSS}$$

New transport infrastructure or resilience interventions such as adaptation measures can reduce the expected value of losses, or disbenefits, from incidents, either through:

1. Reducing the likelihood of a risk materialising and impacting the transport network;
2. Reducing the loss if a risk does materialise (i.e. reducing journey time impacts and value added losses in the supply chain and wider economy).

Capturing avoided losses is consistent with Three Dividend frameworks for measuring resilience, as set out in Defra's Climate Adaptation guidance (2025). Two stylised models of total public value best illustrates the social welfare impacts as a result of a transport intervention reducing the size of potential losses following an improvement in resilience (see below):¹⁴

- A Do Nothing Option (where no additional resilience intervention is undertaken) and a Do Something Option (where an intervention to improve resilience is undertaken).
- A sudden drop in social welfare following a shock (driven by reduced traffic flow and business value-added). Due to the stronger level of preparedness, the Do Something results in a lower initial fall in social welfare, compared to the Do Nothing.
- Stronger resilience leads to social welfare recovering to the BAU level more quickly in the Do Something compared to the Do Nothing (as traffic flow and business value-added returns to normal levels).
- The area under the curve for each option represents the overall social welfare during the appraisal period. Through helping to avoid additional social welfare losses associated with the Do Nothing, the Do Something results in an improvement in public value.

Figure 16. Conceptual model for calculating Resilience and Avoided Losses. Source: PA Consulting.

¹⁴ These models are consistent with National Highways Resilience Technical Annex (2022a), Ganin et al. (2017), Kurth, Ali et al. (2020) and Zhang et al. (2023) which apply an avoided loss framework within a transport context. In this literature the 'avoided loss' in question is avoiding disruptions to transport user journey times or associated value added (see Section 4.4.2 for a more detailed explanation).

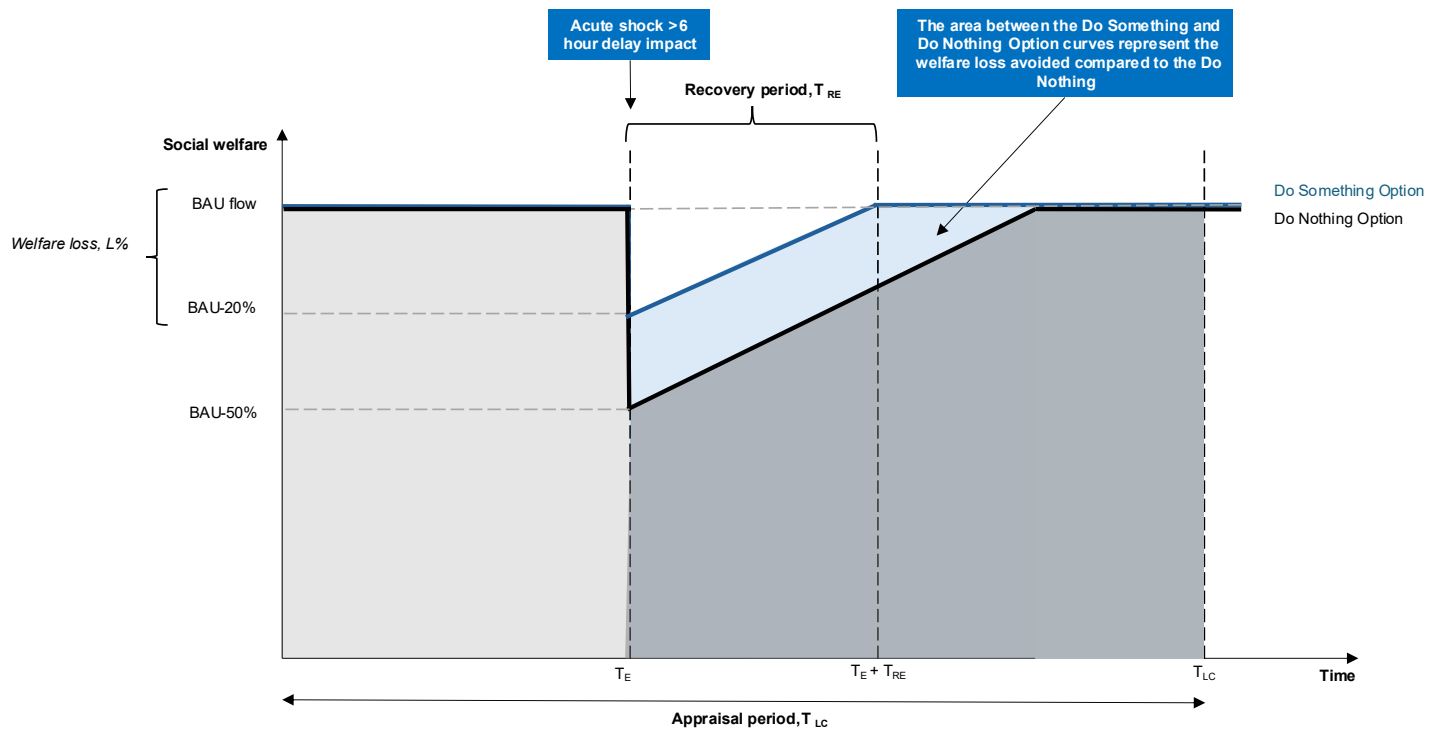
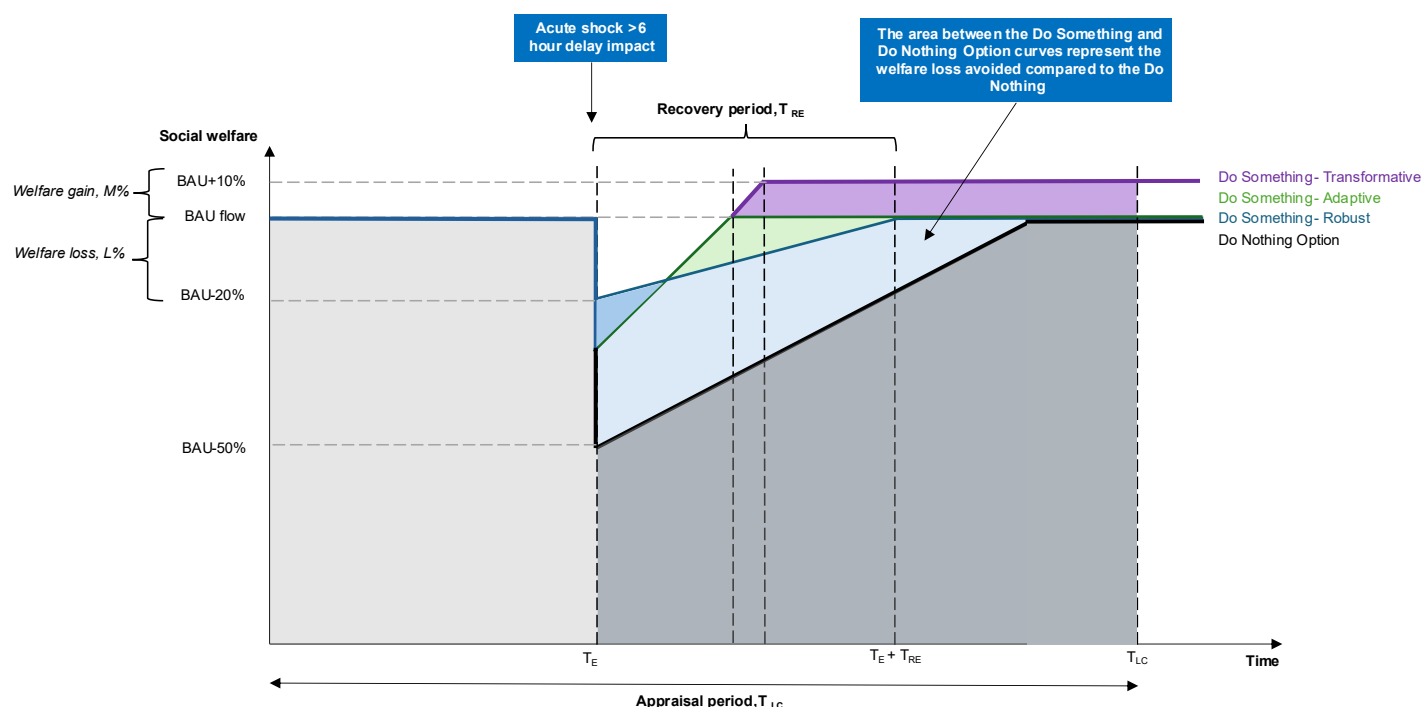


Figure 17 expands on this model to demonstrate how alternative Do Something Options resulting in different resilience measures could be compared and appraised:

- Robust, adaptive, or transformative options are modelled which result in different pathways for social welfare impacts following a shock. A Robust Option will reduce the initial loss following a shock better than alternative options, but not impact the rate of recovery.
- An Adaptive Option may suffer a bigger initial loss than a Robust Option, but social welfare will recover more quickly.
- A Transformative Option contains the resilience measures included in the Adaptive Option, but also includes transformational improvement to enable a permanently higher level of social welfare to be achieved (for example, enabling permanently lower journey times).

Calculating the 'avoided loss' involves mapping the social welfare under Do Nothing and Do Something Resilience Options, then calculating the difference in "area under the curve". In the below example, the "Transformative Do Something" provides the greatest improvement in social welfare, followed by the "Adaptive Do Something" and the "Robust Do Something", compared to the Do Nothing. However, ideally, resilience options are a combination of robust, adaptive and transformative measures.

Figure 17. Conceptual model for calculating Resilience and Avoided Losses with variations in "Do Something" Options. Source: PA Consulting.



Note: these frameworks do not include the impact of chronic risks such as infrastructure degradation. See Figure 19 in Section 4.4.5 for this framework amended to capture chronic risks.

Appraising resilience in a transport context based on an expected value avoided loss framework faces several outstanding analytical challenges. Its application is constrained by the availability of reliable data, particularly on probabilities of acute risks to the transport system. Alternative approaches to traditional CBA have also been considered in developing this framework (see below).

4.3.3 Alternative Approaches to Traditional CBA

While CBA is the foundation of the conceptual framework, the literature highlights a range of alternative approaches for consideration outside standard TAG applications. Whilst the drawbacks of these approaches mean they should not provide the main Value for Money frame of reference, these could help inform complementary appraisal methods (such as informing supplementary risk and uncertainty analysis). An assessment of alternative approaches is presented in Table 14, below:

Table 14. Assessment of Alternative Vfm frameworks

Approach	Description	Assessment	Potential application
Adjusted CBA	Scenario-based CBA , which may be combined with regret analysis or breakeven analysis. This may involve presenting a range of BCRs or presenting alternative decision information to a BCR.	Useful for exploring performance under multiple futures and informing decision making under alternative optimisation rules. However, most transport schemes will need to demonstrate optimal Vfm .	Enhanced scenario analysis identified as a risk and uncertainty tool (see Section 4.4.4) <i>e.g. Argyroudis (2021) use of breakeven analysis to inform design thresholds for acceptable values of the resilience metrics, e.g. "maximum risk tolerances"</i>
Resilience standards	Defines thresholds or performance criteria that transport infrastructure should meet to ensure adequate	Standards are most practical for chronic risks. However, defining the "right" standard to apply may naturally require	Optimal resilience standards assessed in appraisal of chronic risks (see Section 4.4.5)

	preparedness and adaptability in the face of potential shocks.	conventional CBA techniques.	<i>e.g. The Rail Delivery Group's Rail Resilience Project (2021) and its Codes of Practice and associate Tools for Resilience (2025).</i>
Cost effectiveness analysis (CEA)	Compares costs relative to achieving established resilience thresholds when monetisation is impractical.	Useful where monetisation of benefits is impractical to identify the most cost-effective way to meet a predefined level of resilience . However, the lack of widespread resilience thresholds limits general applicability.	Potentially combined with resilience standards in appraisal of chronic risks (see Section 4.4.5) <i>e.g. The Rail Operational Risk & Resilience Index (RORRI), developed by the Rail Safety and Standards Board (RSSB, 2025) uses strategic risk indexing.</i>
Multi criteria frameworks	Structured approach to combine qualitative and quantitative evidence across multiple objectives including resilience, safety, and environmental factors.	Useful for early-stage appraisal and option ranking , however including qualitative factors, equity considerations, and stakeholder preferences mean weightings can be subjective.	A potential framework to deploy in non-monetised assessment (see Section 4.4.3) <i>e.g. The Network Rail Exeter to Newton Abbot Geo-Environmental Resilience Study (2016) following the Dawlish Rail line collapse.</i>
Discount rate	Potential to adjust the STPR for resilience considerations (i.e. reflecting how future benefits and costs are valued relative to present impacts).	Assumes that resilience investments reduce future risk and therefore justify a lower rate. Issues such as double discounting could cause inconsistency and incomparability across projects.	Not recommended until further evidence emerges. Should be reviewed following HMT Green Book discount rate review.
Decision making under uncertainty	Uses techniques like real options, adaptive pathways, robust decision-making, and portfolio analysis to address deep uncertainty .	Strong theoretical underpinnings however many methods are resource intensive , and few have been applied to transport schemes in practice.	Applicable in risk and uncertainty analysis in certain contexts (see Section 4.4.4) <i>e.g. The Thames Estuary 2100 project use of adaptive pathways (Environment Agency, 2023; JBA Consulting, 2024).</i>
Advanced decision-making frameworks	Uses large-scale, complex and dynamic models to bring together impact assessment and probabilistic risk tools to quantify impacts across multiple scenarios.	Whilst may bring optimal elements of CBA and Risk and Uncertainty approaches together, are often complex and create a significant data and analytical requirement unlikely to be proportional in most contexts.	Requires further research to develop agreed and feasible approaches. <i>e.g. The Resilience and Disaster Recovery (RDR) Tool Suite (US Department of Transport, Volpe Center, 2022)</i>

4.4 Proposed Framework for Appraising Resilience

4.4.1 Strategic Assessment and Scope of the Appraisal

The first step in appraising resilience is to establish a clear and proportionate scope. This ensures that subsequent analysis is targeted at the most material risks and outcomes, aligns with strategic objectives, and integrates effectively with the wider TAG framework.

Defining the Appraisal Boundary

The strategic assessment in the strategic case should set the appraisal boundary for the economic case and be articulated across four dimensions:

- **Resilience ‘for what’:** Clarify the outcomes that matter for transport decision-makers, such as network availability, recovery time, and journey times.
- **Resilience ‘of what’:** Identify the system layer under consideration, whether an individual asset, a route, a sub-national network, or the national network (i.e. defining ‘route’ or ‘network’ resilience). Its interdependencies, value chains and critical components (Field et al, 2024).
- **Resilience ‘to what’:** Specify the relevant risks, distinguishing between acute shocks, requiring immediate response, and chronic stresses that degrade performance over time.
- **Resilience ‘for whom’:** Define the affected stakeholders, including transport users, operators, and dependent sectors, and note any distributional considerations for vulnerable groups.

For example, a narrower system with local users impacted may require smaller-scale local-based appraisal approach, whereas a sub-national network impacting many transport users may require deployment of a regional transport model. The resilience ‘to what’ response will shape the definition of any scenarios employed. In addition, whether the key risks are acute or chronic in nature will define different pathways for the appraisal.¹⁵

This Resilience Four Questions approach, or alternative maturity model frameworks (such as RSSB, 2025) can help to identify and prioritise the **resilience needs of the transport system** under consideration, shaping the extent of resilience improvement that can be achieved. If resilience of the transport network drives the case for change for the scheme, this should be codified in the strategic objectives (see next section).

Resilience threshold measures described in Section 4.2.3 could be deployed in the strategic assessment to ascertain the potential materiality of resilience impacts. If resilience is not expected to be a material consideration, appraisal of these impacts will not be required.

Appropriately Codifying Resilience in Strategic Objectives

The depth of the economic appraisal undertaken will be shaped by whether resilience of the transport network is the primary purpose of an intervention, whether it is a secondary/supporting objective or if it is not an objective but a consequential impact:

- **Resilience as the primary objective:** Interventions on the transport network primarily designed to prevent, withstand, recover from, or adapt to potential acute or chronic risks. *Example: Thames Barrier 2100*
- **Resilience as a secondary/supporting objective:** Interventions on the transport network that target other objectives, but may also deliver resilience as a co-benefit. *Example: Additional runway at London Heathrow*
- **Resilience as a consequential impact:** Interventions on the transport network that do not have an objective to improve resilience but may lead to material resilience impacts (either beneficial or adverse).¹⁶ *Example: Lower Thames Crossing*

The **primacy of resilience in the strategic objectives** should be a key factor influencing the proportionality of the analytical effort undertaken. Where resilience is a primary objective, a detailed monetised assessment and quantification of the resilience impact will likely be required. Where resilience is a supporting objective, supplementary risk and uncertainty analysis is likely warranted (for example,

¹⁵ The economic assessment framework set out in Section 4.2 – 4.4 generally assumes the key risks are acute in nature, whilst an approach for chronic risk assessment, which relies on similar underlying principles is described in Section 4.5.

¹⁶ The scheme Theory of Change and Economic Narrative could be reviewed and any resilience outcomes and impacts incorporated to highlight any material resilience impacts

additional scenario analysis). Where resilience is a consequential impact, impacts may be assessed through non-monetised assessment.

Interventions that include resilience as a spending objective should demonstrate alignment with existing resilience strategies and policies in the **strategic fit** section of the strategic case.

Identifying Transport Strategies for Delivering any Resilience Objectives

The options available for delivering the strategic objectives are set out in the economic appraisal. Where resilience is reflected in the spending objectives, in preparation for this it is important to consider the **appropriate range of potential strategies as set out in the ‘resilience cycle’** (see Section 2.2.1). This includes actions to anticipate, prevent, prepare or mitigate acute risks to the transport network before the shock, alongside strategies to respond, adapt, recover, learn and transform following the shock. Some of these areas contribute to reducing or preventing the risk impacting the transport network and others contribute to building ‘adaptive capacity’.

The strategic assessment plays an important role in defining the **‘choice architecture’ for decision-makers** that the appraisal will inform. The allocation of responsibilities for resilience of the transport network across departments and organisations may naturally constrain which resilience options can be considered in the appraisal. For example, a scheme targeting flood-prone infrastructure may appraise mitigation and recovery options only, while a digital transport system may appraise response and learning options (e.g. from cyber threats). In doing so, the strategic assessment may need to clearly articulate which aspects of the resilience cycle are within the remit of the economic appraisal.

This assessment may also inform the extent to which scheme-level appraisal is the most appropriate device for choosing between options for delivering resilience. For example, if many system-wide interdependencies and cascading factors that exist, it may be appropriate to consider **programmatic or portfolio-level appraisal** approaches to appraise resilience at a wider system-level.

4.4.2 Economic Appraisal – Monetising Avoided Losses

If the strategic assessment determines that resilience is a relevant strategic objective and/or resilience impacts could potentially be material, the economic appraisal should look to capture these impacts, if possible, through **monetised appraisal**.

Section 4.3.2 sets out a generalised framework that when **risk probabilities can be robustly estimated**, there is the potential to include avoided loss impacts in Net Present Social Value (NPSV) analysis through an expected value framework: potential loss multiplied by the likelihood of the risk materialising.¹⁷ This section takes this approach forward in a transport context, describing a framework for appraisal that could be adopted in future TAG guidance. Given the significant cost associated with model runs, this framework aims to achieve a ‘Minimum Viable Product’ rather than ‘Gold Plated’ appraisal approach.

Appraisal Approach and Parameters to Quantify Acute Risks

Appraisal should be designed to clearly capture the impact of the shock that is being appraised, where on the transport network will be affected and the likelihood of the shock occurring.

The monetisation approach should start with **identifying the critical points on the transport network** where acute shocks are expected to have the biggest impact. This might be locations which are most vulnerable to a shock, or bottlenecks on the network that amplify shocks that affect the network directly elsewhere. High-level network analysis by transport modellers should be undertaken to identify these locations. This should narrow the geographic appraisal boundary for the appraisal to a proportional level, whilst recognising that cascading nature of shocks and interdependencies with other parts of the transport system may require the geographic appraisal boundary to be extended to capture these impacts. Based on this analysis, it should be determined whether route or network resilience should be appraised, or both.

The nature of the acute risks being analysed by the appraisal should have been defined in the strategic assessment (see Section 4.4.1) and these **acute risks may need to be further parameterised** in the economic appraisal to allow them to be assessed (for example, quantifying the length of the delay

¹⁷ When risk probabilities cannot be estimated, an assessment of monetised losses should still take place; which could inform non-monetised impact ratings (see Section 4.4.2), or probability switching values in the risk and uncertainty analysis (see Section 4.4.3).

modelled, and temporal considerations such as time of day, and seasonal effect). The shock definition should be in line with the thresholds set out in Section 4.2.3 (e.g. a delay duration of six hours or more) to place limitations on the number of model runs required.

In summary, resilience interventions can reduce the expected value of losses in two ways:

1. Reducing the probability of a risk materialising and impacting the transport network (**probability reduction**).
2. Reducing the losses to transport users and the wider economy if a risk does materialise – reducing journey time impacts and lost value-added in the supply chain (**impact reduction**).

Probability Reduction

The likelihood of the shock materialising on the transport network should be quantified in the Do Nothing and Do Something options. Multi-year analysis of incident durations can be undertaken. Strategic analysis may indicate, for example, that on average a six-hour delay occurs four times a year in the Do Nothing Option, but occurs two times a year in the Do Something Option because of greater capacity added. This will inform the number of incident scenarios that should be run across the appraisal period. Where evidence on reduced incident delays is not available, or it is ambiguous, an unchanged probability should be assumed. Cabinet Office Resilience Framework (2023a) concepts such as the **Reasonable Worst Case Scenario (RWCS)** and risk probabilities provided in the **National Risk Register** can also support acute risk likelihood estimation.

Impact Reduction – Appraising Quantity Changes

To quantify the avoided loss, social welfare should be measured in a “with scheme” and “without scheme” option under both a “shock” and “without shock” scenario. This is in line with the National Highways Resilience Technical Annex (2022a) approach for calculating resilience benefits when incident frequency is affected.¹⁸ The literature suggests two main welfare impacts from changes in resilience where appraisal should be considered in line with Figure in Section 4.2.2:¹⁹

- 1) **Transport user impacts (‘Direct’ Impact, Level 1 / Level 2)**. Acute shocks can result in significant delays to transport users, which are reflected in higher journey times and vehicle operating costs.²⁰ An increase in costs for transport business or freight users will also lead to additional welfare loss due to the presence of imperfect competition.
- 2) **Impacts from changes in value added in the supply chain and wider economy (‘Wider’ Impact, Level 3)**. Unanticipated and short-run disruptions means that the current use of capital and labour is suddenly made idle and are not redeployed in alternative ways, resulting in a loss of value-added.

Appraising Quantity Changes – Transport User Impacts

Transport models should be run to **estimate the losses to user’s journey times and vehicle operating costs** that the scheme can deliver when an acute shock is applied. Stimulating a shock will differ across different transport models and according to the geographic boundary of the appraisal. For example, route resilience for a highway scheme could be appraised by removing affected links from a Regional Traffic Model and simulating the impact on user journeys. Variable demand modelling should be avoided to better reflect short-run disruption impacts.

The basis for transport user impacts from acute shocks is the National Highways Resilience Technical Annex (2022a). Wider literature such as Ganin et al (2017) and the DfT Winter Resilience in Transport (2011) study find significant journey time costs from acute shocks²¹.

To fully capture the transport user impacts, this analysis would include the full extent of the relevant network in the “with” and “without” scheme option. Transport user impacts are driven by both the

¹⁸ The NH appraisal manual method for incident frequency being unaffected does not consider the difference in costs in the “without shock” scenario between the “with scheme” and “without scheme” options and so should not be followed.

¹⁹ These two main impacts have been identified from the literature review – however, this is not exhaustive and resilience impacts may cover broader areas such as safety, environmental or social impacts. The impacts to be analysed should be selected based on the appraisal context.

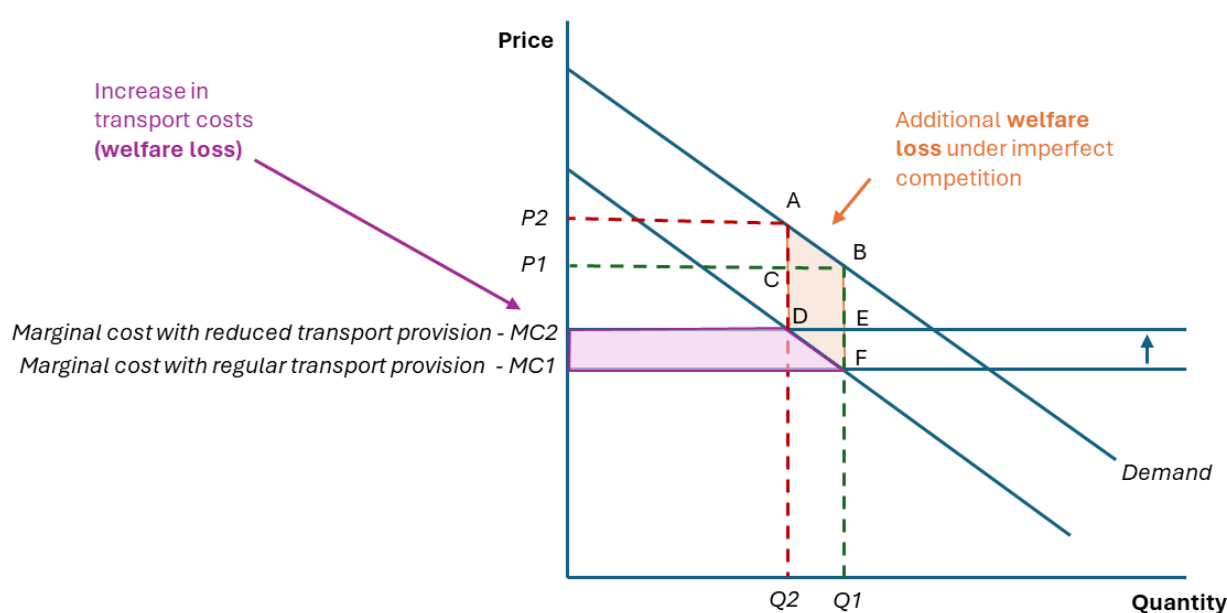
²⁰ These delays may also cause higher accidents and GHG emissions, but these are expected to be less significant and it may not be proportional to appraise these.

²¹ In addition, Hallegatte (2014) found that transport perturbations on transport users following the Northridge Earthquake accounted for 39% of total losses. TRL (2018) found direct user costs of £300,000 (2004 prices) from road closures triggered by 2004 landslides on the A83 Glen Kinglas to Cairndow.

enhanced capacity that the scheme delivers to manage a shock and the numbers of road users affected. Examining the latter driver – in the case of a new transport link (e.g. a new road) that allows more journeys to be completed, the losses that are experienced by these users in the “with scheme” option following a shock would represent a loss in social welfare (as these journeys would not occur in the “without scheme” option). These losses could be counteracted by the welfare gains experienced through fewer journeys potentially being impacted on the existing network in the “with scheme” option. Whilst this could be analytically demanding, further research could provide ‘look-up tables’ to expedite the analysis (see Section 4.5.2).

The **presence of imperfect competition creates an additional welfare loss** from an increase in marginal costs for business users impacted by the shock. Figure , below, shows how an acute shock acts as a negative supply shock and causes an increase in transport costs to firms, leading to the firm decreasing output (from Q_1 to Q_2) and increasing price (from P_1 to P_2). Whilst the increase in transport cost is captured in transport user impacts (see above), the additional welfare loss under imperfect competition is not. Present TAG advice suggests that an uplift of 13.4% is applied to business and freight user journey benefits (Oxera, 2023).

Figure 18. Efficiency loss caused by a transport disruption. Source: PA Consulting analysis.



Appraising Quantity Changes – Impacts from Changes in Value Added in the Supply Chain

Whilst acute shocks impose additional costs on transport users, they may also **impose additional costs on firms** dependent on the transport network.

Cost Benefit Analysis in line with TAG does not traditionally capture these impacts as it assumes induced quantity changes are of no additional cost or benefit, because resources can move from one productive use to another equally valuable use. When transport is a material business input, firms are expected to build day-to-day variability of the transport network (as measured through ‘reliability’ appraisal) into business processes (for example, holding buffer stocks and inventory levels that insure against incremental delays) (Harrison et al., 2019).

However acute shocks are sudden, severe and outside routine variability, meaning firms may fail to accurately predict them or fully prepare for them²². The failure to self-insure against acute shocks means that when one occurs capital and labour now made idle cannot be quickly redeployed in alternative ways, resulting in a loss of value-added.

For example, manufacturers that rely on just-in-time (JIT) delivery of raw materials or components may now miss delivery windows and face production stoppages which typically assumes a relatively stable environment (Choi et al., 2023). Choi et. al. also confirm that geographic distance and lead times are

²² Research on 450 UK SMEs revealed that 78% experienced major supply chain disruptions, yet less than 25% had pre-existing risk management frameworks leading to the majority adopting reactive measures rather than proactive contingency planning (Onyeunuforo et al., 2024). Firms may fail to fully prepare as investments in redundancy or alternative transport modes offer uncertain returns compared to immediate cost savings (Acemoglu & Tahbaz-Salehi, 2025; Baldwin & Freeman, 2022).

relevant factors firms use to set JIT buffer levels, and that disruption beyond these buffers typically leads to stockouts or production delays. The cost impact on firms as delays unfold is not linear – Ivanov (2021) finds a disproportionate rise in costs with delay length after an initial tolerance period depending on the preparedness and risk exposure of the system. For service businesses, workers stuck in congestion cannot access their workplaces, rotas and resource plans cannot be adapted in time and this leads to reductions in output. These impacts can propagate through further through the supply chain (indirect effects) (Acemoglu & Tahbaz-Salehi, 2024).

The structural rigidities associated with the inability to redeploy capital and labour following an acute shock can be seen from the Jaguar Land Rover (JLR) cyber attack in 2025 (see below).

Applied Example: JLR Cyber Attack

The cyberattack targeting JLR in 2025 halted production for five weeks, disrupted dealer systems, and cascaded through a supply chain of over 5,000 firms. The estimated economic impact from reduced GVA was £1.9 billion, with around half this total made up of losses in the local supply chain. The presence of significant fixed costs (expensive capital machinery) magnified firm-level output losses during shocks, creating negative multiplier effects in subsequent supply chain tiers.

In the JLR example, the production output was irretrievably lost, so the loss of value added is close to the value of output lost.²³ This type of impact is particularly relevant for the delivery of goods in a just-in-time production process, but would also apply to the delivery of services (e.g. service sector employees missing appointments etc.).

Economic studies, often using Input-Output Tables have been used to appraise these supply chain impacts in the transportation sector following a shock. Whilst these studies cannot be directly compared, it suggests that output losses from an acute shock are significant and could range between £50m-£1bn depending on impact severity and modelling methodology. Input-Output approaches typically provide large estimates (between £300m-£1bn) and do not necessarily fully adjust for displacement, leakage and substitution effects and so should be treated with caution. Authors seeking to quantify a more limited set of costs using welfare-based analysis have found lower impact – typically ranging between £50m-£150m. For example Tran et al. (2025) estimate the economic costs of the 2021 six-day blockage of the Suez Canal at £67m. The authors captured ship costs, environmental costs and inventory-carrying costs and assumed no loss of output in production of the cargo that was being carried. Table 20 in Annex B summarises these examples in more detail.

Other Potential Quantity Changes – GVA Impacts in the Wider Economy

Methods involving Input-Output tables may not fully capture the full range of dynamic pathways through which acute shocks involving the transportation sector propagate throughout the economy. For example, impacts on earnings through the consumption channel are captured with GDP assessment approaches (DfT, 2019). These impacts may be material in certain contexts, for example when observing a large number of leisure travellers.

The literature supports use of large-scale wider economy models such as Computable General Equilibrium (CGE) models to estimate losses to GDP that may arise through these wider range of pathways. For example, Zhang et al. (2023) apply a CGE model to capture how transport disruptions propagate through labour markets, goods supply chains and household consumption, ultimately affecting regional and national GDP. Their findings highlight that resilience interventions can avert significant GDP contraction under severe disruption scenarios. Similarly, Xie et al. (2014) quantifies economic costs of the 2008 Wenchuan Earthquake through a CGE model, highlighting sectoral GVA losses to the Transportation, Post & Telecommunications sector of 840bn Yuan.

Other Potential Quantity Changes – Total Value Systems Approach

‘Total value systems’ potentially provides an alternative strategic-level modelling approach to detailed application of traffic and economic models (Field and Look, 2018). Total value systems are scenario-agnostic and provide an understanding of the system, its value chains, its critical functions and interdependencies. By examining these interconnected components, decision-makers can identify critical dependencies and understand how the performance of one sector may impact others, creating a clearer

²³ This should be take account of the share of output that is value-added vs intermediate consumption. This share will depend upon which parts of the value chain are analysed. It might be most practical to include impacted users plus first tier suppliers rather than extending to all domestic economic activity (where intermediate consumption would reflect imports only).

picture of potential strengths and vulnerabilities within the system (Betts and Buzzanell, 2022). Specific scenarios can be run alongside scenario-agnostic consequence-based analysis which appraises the impact of losing a specific system node.²⁴ This approach has the potential to capture both Direct Transport User Impacts and Wider Economic Impacts. Further research is required to understand potential application of this approach to transport (see Section 4.5.2)

Impact Reduction – Appraising Price Changes

During normal network conditions, standardised values of time reflect the trade-off between the time taken and cost of routine travel, in line with DfT's TAG Unit A1.3 (2025b).

However, during unexpected and prolonged disruptions, there is evidence that the perceived cost of delays for transport users is increased.²⁵

Congestion multipliers have been derived to reflect the higher disutility of time spent in congested conditions compared to free-flow travel.

The Institute for Transport Studies (ITS) Leeds scoping study for DfT (2025) provides a comprehensive review of how congestion influences the Value of Travel Time (VTT). Evidence from the 2014/15 national VTT study indicates that VTT varies significantly across traffic conditions. Specifically, values differ between light congestion, and heavy congestion scenarios, with congestion multipliers reported in the range of 1.4 – 1.8 for light congestion and 2.7 – 4.0 for heavy congestion, depending on journey purpose (commute, business, non-work). These findings suggest that time spent in severe congestion can be valued up to four times higher than time in free-flow conditions. As congestion intensifies, the marginal disutility of time rises because travellers lose flexibility to reschedule activities, and the opportunity cost of time becomes greater. Wardman and Ibáñez (2012) identify a graded congestion multiplier for motorists, applicable across congestion levels from free flow to gridlock. Smith and Tenekeci (2022) suggests that user valuations of time under severe disruption could be several multiples higher than those captured in present TAG values, particularly for freight users. Congested time is also perceived as qualitatively worse due to stress and unpredictability, reinforcing willingness-to-pay for time savings.

Whilst the DfT's report on "Congested Values of Travel Time" (DfT, 2019a) highlights how these uplifts could be incorporated within appraisal tools such as TUBA, TAG has not adopted congestion multipliers due to unresolved issues. This includes potential double-counting with reliability and crowding, challenges in defining congestion consistently, and equity concerns. At present, it is therefore recommended that resilience appraisal of transport user impacts uses standardised values of time to ensure consistency with existing TAG guidance.

4.4.3 Economic Appraisal – Non-Monetised Assessment

If the strategic assessment determines that resilience is not a relevant strategic objective, or where data is not available to conduct monetised assessment, it may be more proportionate for the economic appraisal to capture impacts through **non-monetised assessment**.

TAG's Unit A4.1 Social Impact Appraisal (2022) and Unit A3 Environmental Impacts (2025) already provide an existing conceptual framework for non-monetised assessment. This is applied in areas such as security, severance, accessibility and personal affordability impacts and this can be extended to the appraisal of resilience. DfT guidance states that non-monetised assessments should focus on the **directionality of the impact** (i.e. whether the difference between the without-scheme and with-scheme cases will be better, worse or neutral) and the **order of magnitude size of the impact** (i.e. whether the impact would be slight, moderate or large).

In line with existing guidance, scorings should be undertaken for key sub-factors where possible to inform the overall rating. The relevant core sub-factors suggested below are in line with the monetised

²⁴ Field et al (2024) sets out the total value systems approach to a large UK airport where value chain mapping and critically analysis identified essential functions (such as power, data and transport access) and showed how their failure would cascade across operations, pinpointing vulnerabilities.

²⁵ Rahimi et al. (2020) found that rail passengers were highly sensitive to recovery time during unplanned outages. Delays were found to increase willingness to pay for alternatives as risk aversion increases and flexibility to reschedule activities reduces, leading to higher values of time. Jenelius et al. (2020) find that the average user cost per hour delay increases with the delay duration, so every additional minute of delay comes with a higher user cost. These marginal cost of delays increases happen because transport users lose the ability to reschedule activities. This is supported by metro disruption research (Zhang et al., 2023; Liu et al., 2023) demonstrating the non-linear increases in perceived journey time costs and mode-switching behaviour during extended outages.

assessment impact areas: transport user impacts and wider economic impacts. However, this could be supplemented through additional bespoke resilience impacts where these are justified (for example, mitigated environmental impacts).

Impact Directionality

The **impact directionality scorings** that should be used for non-monetised resilience appraisal are:

- the assessment is likely to be **neutral**, if the assessment is neutral for all or most of the sub-factors, or improvements on some sub-factors are generally balanced by deterioration on others;
- if the change in impact across the sub-factors is, on balance, for the better, the assessment is likely to be **beneficial**,
- if the change in impact across the sub-factors is, on balance, for the worse, the assessment is likely to be **adverse**.

Impact Size

The **impact size scorings** that should be used for non-monetised resilience appraisal are:

- the assessment is likely to be **slight** (beneficial or adverse) where the scheme is not expected to materially affect either the probability of severe acute shocks occurring on the transport network, resulting in over six hours of delay, or the impact if an acute shock did occur on the network (as measured by direct transport user or wider economic impacts).
- the assessment is likely to be **large** (beneficial or adverse) where the scheme is expected to significantly affect either the probability of severe acute shocks occurring on the transport network, resulting in over six hours of delay, or the impact if an acute shock did occur on the network (as measured by direct transport user or wider economic impacts).
- the assessment is likely to be **moderate** (beneficial or adverse) in all other cases.

If a monetised assessment has taken place, but robust probabilities cannot be estimated, this information should inform the non-monetised assessment and impacts can be reported as a non-monetised impact, with an illustration of the potential avoided loss in quantitative terms.

To aid decision-makers in applying non-monetised assessment, further guidance on supporting indicators can support the impact size scoring. Potential further guidance that could be provided in TAG is set out below, reflecting the most credible indicators used today in line with the conceptual framework outlined above.

Table 15. Illustrative non-monetised indicators and impact size

Impact size	Illustrative non-monetised metrics/indicators
Slight	<p><i>Negligible or minor avoided welfare impacts from the intervention against the baseline. For example:</i></p> <ul style="list-style-type: none"> • <i>Probability of severe acute shocks hitting the network remain at a broadly similar level</i> • <i>Transport User Impacts from severe acute shocks expected to remain broadly similar on the route itself and network-wide:</i> <ul style="list-style-type: none"> - <i>The peak-to-trough transport flow impact on the route/wider network following shock remains broadly similar</i> - <i>The recovery period for transport flow on the route/wider network to return to a normal level following shock remains broadly similar</i> - <i>The number of people impacted by shock on the route/wider network remains broadly similar</i> - <i>The transport link does not become a materially more dependable diversion route (e.g. the same number of alternative routes are available to transport users following shock)</i> • <i>Wider Economic Impacts from severe acute shocks remain broadly similar:</i> <ul style="list-style-type: none"> - <i>The share of business and commuting users heavily affected by a shock is broadly average.</i> - <i>Major UK businesses, industries or supply chains do not significantly depend on the route that is significantly impacted following a shock</i> • <i>Other bespoke impacts from severe acute shocks remain broadly similar (mortality impacts, environmental impacts, emergency costs etc).</i>
Moderate	<p><i>Noticeable or moderate avoided welfare impacts from the intervention against the baseline. For example:</i></p> <ul style="list-style-type: none"> • <i>Probability of severe acute shocks hitting the network changes moderately</i> • <i>Transport User Impacts from severe acute shocks changes moderately – on the route itself and network-wide:</i> <ul style="list-style-type: none"> - <i>The peak-to-trough transport flow impact on the route/wider network following shock changes moderately</i> - <i>The recovery period for transport flow on the route/wider network to return to a normal level following a shock changes moderately</i> - <i>The number of people impacted on the route/wider network by shock changes moderately</i> - <i>The transport link becomes a moderately more/less dependable diversion route (e.g. leads to an improvement of one or more alternative routes that are available to transport users following a shock).</i> • <i>Wider Economic Impacts from severe acute shocks changes moderately:</i> <ul style="list-style-type: none"> - <i>The share of business and commuting users heavily affected by a shock is above average.</i> - <i>Major UK businesses, industries or supply chains frequently use the route that is significantly impacted following a shock</i> • <i>Other bespoke impacts from severe acute shocks change moderately (mortality impacts, environmental impacts, emergency costs etc).</i>

Impact size	Illustrative non-monetised metrics/indicators
Large	<p><i>Significant or material impacts from the intervention against the baseline. For example:</i></p> <ul style="list-style-type: none"> • <i>Probability of severe acute shocks hitting the network changes by an order-of-magnitude level</i> • <i>Transport User Impacts from severe acute shocks changes by an order-of-magnitude – on the route itself and network-wide:</i> <ul style="list-style-type: none"> - <i>The peak-to-trough transport flow impact on the route and/or wider network following shock changes by an order-of-magnitude</i> - <i>The recovery period for transport flow to return to a normal level on the route and/or wider network following shock changes by an order-of-magnitude</i> - <i>The number of people impacted on the route and/or wider network by shock changes by an order-of-magnitude</i> - <i>The transport link becomes an extensively more/less dependable diversion route (e.g. leads to an introduction/closure of a major alternative route / multiple alternative routes that are available to transport users following a shock).</i> • <i>Wider Economic Impacts from severe acute shocks changes by an order-of-magnitude:</i> <ul style="list-style-type: none"> - <i>The share of business and commuting users heavily affected by a shock is significantly above average.</i> - <i>Major UK businesses and industries or supply chains critically depend on the route that is significantly impacted following a shock</i> • <i>Other bespoke impacts from severe acute shocks change by order-of-magnitude (mortality impacts, environmental impacts, emergency costs etc).</i>

Bespoke resilience impacts outside this framework should be considered when there is strong evidence on their existence. For example, this might include emergency response impact costs for government and public-sector organisations, cost of harm impacts such as fatalities or casualties (as measured through QALY methods), environmental impacts (such as increased carbon emissions or natural environment effects) or dynamic wider economic impacts.

Decision-makers should be able to use judgement to classify order of magnitude impacts through this approach. Over time, greater quantification could be added to codify the relationship between acute shocks of specific thresholds²⁶ and the impact categories above, which may vary according to the transport context of the scheme (mode type, route importance etc). Further details on recommended quantitative look-up tables are summarised in Section 4.5.

4.4.4 Risk and Uncertainty Analysis

The significant risks and uncertainties associated with appraising resilience in the transport context means that **additional emphasis should be placed on the risk and uncertainty analysis** in shaping the Value for Money assessment.

If a monetised assessment has taken place, but probabilities cannot be robustly estimated, this information should flow into the risk and uncertainty analysis to inform a **probability switching value**.

Probability Switching Value

TAG Value for Money guidance (DfT, 2024) defines a switching value as “*representing the extent to which the Present Value of Benefits, or the Present Value of Costs would need to increase or decrease for the VfM Category of the proposal to change*”.

A probability switching value adapts this concept to resilience appraisal. It calculates the probability that acts as a ‘plug value’ in the appraisal using an expected value framework. This reflects the probability of the risk that the decision-maker would need to believe for the intervention to represent a minimum desired level of Value for Money. This allows decision-makers to use informed judgement whether to progress the intervention, making appropriate trade-offs between risks to resilience and other risks in

²⁶ For example, Network Rail is currently considering alternative threshold measures using metrics such as: Impact in delay minutes, impact in delay cost, train performance, service availability, recovery handback times and recovery times.

their portfolio. These values can convey important information to decision-makers on risk, even with a complete absence of any robust risk information.

It is important to distinguish between two contexts when applying probability switching values:

1) Resilience improvement considered in isolation

This applies when the resilience intervention is appraised as a standalone option (e.g., a flood defence upgrade or cyber resilience measure). The relevant formula for calculating the switching value in the case when the minimum acceptable level of VfM is reflected in a Benefit Cost Ratio of 1 is:

$$\text{Probability Switching Value} = \text{Present Value of Costs} \div \text{Present Value of Avoided Loss}$$

2) Resilience intervention considered as part of a wider transport scheme

Decision-makers may also wish to understand the probability switching value when the resilience improvement shapes the VfM outcome of the overall transport scheme. Probability switching values can be constructed to estimate the probability of a risk materialising that tips the overall scheme VfM into the next Value for Money category, considering both the additional costs involved in the resilience improvement, and the additional avoided loss that is expected to result. These types of switching value are more complex for decision-makers to understand and interpret and care should be taken when reporting the results. In the majority of cases, it may be most proportional to deploy switching values to examine the incremental VfM offered by the resilience improvement in isolation.

Supplementary Risk Narrative

If risk probabilities can be robustly estimated, this should be accompanied through **supplementary reporting of risk information** in the risk and uncertainty assessment. This should consist of:

- The probabilities themselves should be **communicated prominently**, on parity with other key appraisal metrics (NPSV, BCR etc).
- A **risk narrative** should be provided that transparently articulates the maturity level underpinning the evidence around the probabilities, and any assumptions applied or important context to consider.
- **Citing the evidence** for probabilities includes: historic transport incident frequencies (e.g. TrafficMaster data), acute shock probabilities (e.g. National Risk Register or National Security Risk Assessment). Weaker evidence may include expert judgement or expert panels.

Where possible, it is important combine multiple perspectives, data sources, and judgment to ensure a comprehensive understanding of the risks.

Supplementary 'Decision Making Under Uncertainty' Techniques

TAG Unit M4 (DfT, 2023) suggests a range of scenario analysis, forecasting and sensitivity testing approaches for managing uncertainty within scheme appraisal. When risks are complex, multi-dimensional or highly dynamic in nature, these tools may be insufficient to fully appraise the impact of risk and uncertainty on transport systems. In these specific circumstances, supplementary decision making under uncertainty techniques may be employed. These may include:

- **Adaptive pathways:** When there are significant path dependencies for decision-making, and significant uncertainties that mean risk probabilities are difficult to estimate 'adaptive pathways' can be used. This approach identifies key trigger points and critical thresholds where the current strategic approach becomes unfeasible. This informs a range of possible option pathways over time when decisions should be revisited. Adaptive pathways are described in more detail in Defra's 'Accounting for effects of climate change' Green Book supplementary guidance (Defra, 2024).
- **Real Option Analysis:** ROA is a complementary technique that can be used following an adaptive pathways exercise to appraise and select the highest VfM pathways available. Unlike CBA which assumes a fixed investment path, ROA acknowledges that decisions can be adapted as new information becomes available and uncertainties unfold. It typically requires some quantification of uncertainty to quantify the "option value" associated with the flexibility of decision making in alternative pathways.

- **Alternative decision rules:** Instead of seeking to maximise the NPSV, alternative decision rules such as 'regret analysis' and 'breakeven analysis' could be employed in circumstances where decision-makers have lower levels risk appetite. For example, 'regret analysis' reflects the regret a decision-maker might feel if a chosen project performs poorly under a particular scenario. This approach helps identify transport schemes that do not just maximise VfM on average but offer VfM across a range of plausible futures (US Department of Transport, Volpe Center, 2022).
- **Portfolio analysis** assesses the risks and returns of multiple transport schemes together, enabling more resilient decision-making by diversifying investments and prioritising those that optimise portfolio decision-rules. NIC's *Managing Uncertainty in the Second National Infrastructure Strategy* (2022) suggest a range of pay-off profiles that could be optimised: Robust Investment (low-risk, low-reward), Strategic Bet (high-risk, high-return), The Hedge (insurance-like approach of generating returns when other investments perform poorly).

4.4.5 Appraisal of Chronic Risks

Chronic risks (such as changing rainfall patterns, rising temperatures, coastal erosion, ageing assets, and demographic change) can be distinguished from acute risks in that they may not lead to an immediate shock event and an associated loss, but may gradually erode transport network capacity and resilience over time. If an acute shock does occur on the network, these chronic factors may exacerbate vulnerability and impose greater losses on transport users and the economy.

Whilst the assessment of chronic risks therefore shares some similar characteristics with the assessment of acute risks, it requires a distinctive analytical approach. The proposed conceptual framework for addressing chronic risks is defined in two parts:

1. **If the relationship between chronic and acute risks are known, the assessment of acute risks can be amended to incorporate the impact of chronic risks.** How chronic risks are incorporated will depend on the assessment method:

If a monetised expected value avoided loss approach is adopted

- Transport and economic modelling tools should seek to capture the deterioration in social welfare prior to an extreme event. This may both amplify the loss of social welfare over the duration of the shock and see social welfare return to a lower (or gradually declining) long-run performance level.
- If it is not feasible to adjust modelling tools to reflect declining social welfare, the scenario specification should be amended to include the interaction with chronic risks. For example, the severity of a flooding event may need to be amplified to factor in the quicker run-off through failure of the road surface. Or the frequency of acute shocks impacting the network could be increased.
- Where chronic risks are highly material to the appraisal context, a **total value systems modelling approach** may best capture the interaction between acute and chronic risks as it allows for a deep understanding of the interdependencies between transport and wider systems, its value chains and critical functions.

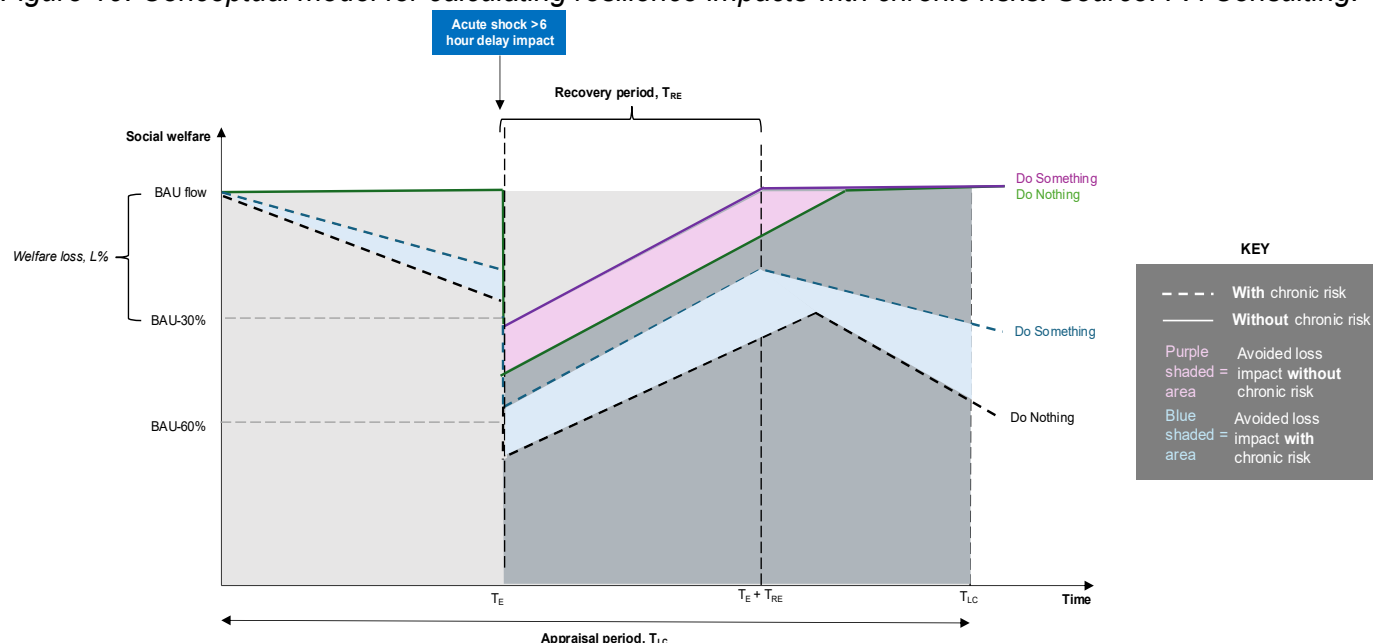
Figure 8 presented a stylised model of social welfare resulting from a resilience improvement on the transport network over time – this can be adapted to also model chronic risks.

In this scenario, a scheme that improves resilience to both chronic and acute risks is modelled (Figure 19, below). Incorporating chronic risks is represented below by the dotted lines, and involves:

- A decline in social welfare over time in the non-emergency periods for both the Do Nothing and Do Something options (for example, reflecting infrastructure degradation and road closures that are required for maintenance works that restrict traffic flow).
- However, the pace of decline in social welfare in the non-emergency period is lower in the Do Something option than the Do Nothing option. In other words, the Do Something scheme leads to an immediate improvement in social welfare up to T_E because it involves greater resilience to chronic risks (for example, re-surfacing with climate-resistant materials that stems decline in asset condition).

- In line with the scenario without chronic risks, the initial loss following the shock is lower in the Do Something than Do Nothing. In other words, in the Do Nothing, chronic risks amplify the loss following the acute shock.
- The greater resilience to chronic risks enables the Do Something option to recover at a faster pace than the Do Nothing option. Chronic risks may also constrain the ability of the Do Nothing to recover to the pre-shock level of network performance and social welfare.

Figure 19: Conceptual model for calculating resilience impacts with chronic risks. Source: PA Consulting.



The difference in the avoided loss impacts between the without chronic risk and with chronic risk scenarios represents the additional avoided loss delivered by the scheme in the context of chronic risks (the blue area minus the pink area above). It should be noted that this illustration and the outcome of a positive social welfare improvement is sensitive to the modelling assumptions used. The above example assumes that chronic risks act on the underlying transport infrastructure state rather than solely the recovered service state. For example, in principle a resilience intervention that accelerates recovery from an acute shock could generate periods of negative incremental welfare relative to the Do Nothing if the latter involves the network recovering to the pre-shock level and chronic risks degrade network performance at a consistent level.

The effects of climate change are an example of a chronic risk that can be appraised in this way. The updated Green Book (HM Treasury, 2026) advises practitioners to take climate change impacts into account within their analytical baseline when doing appraisal. Proposals with a time horizon that end before 2040 should be appraised against a climate scenario in which global temperatures rise by 2°C. Proposals with a time horizon that ends in 2040 or later should also consider a climate sensitivity test of 4°C warming (DEFRA, 2025). The conceptual model above is consistent with this approach – for example, the Do Nothing and Do Something lines (without chronic risks) could represent 2°C warming whereas the Do Nothing and Do Something lines (with chronic risks) could represent 4°C warming.

If a non-monetised approach is adopted

- Non-monetised directional impact scoring and size impact scoring should be adjusted to reflect the role of chronic risks on the losses incurred.
- For example, the presence of chronic risks may lead to tipping points on transport system capacity being breached, exacerbating losses and tipping a 'moderate' impact to a 'large' impact.

2. If the relationship between chronic and acute risks is not known, chronic risks can be appraised separately through a resilience standards approach.

- Resilience standards define thresholds or performance criteria that infrastructure should meet to maintain the safe condition of assets on the transport network ensure adequate preparedness and adaptability in the face of both acute and chronic risks (NIC, 2024).

- Whilst resilience standards are still yet to be universally adopted across UK transport infrastructure, many relevant standards in place today relate specifically to known chronic stressors – changing weather patterns because of climate change, and ageing infrastructure. Examples include the Port Marine Safety Code (DfT, 2025), RDG Resilience Codes of Practice (RDG, 2025a) and DMRB road standards (ITF, 2024)
- The impact of chronic risks can therefore be examined through **appraisal of different levels of asset condition**. Asset condition analysis should appraise a ‘Do Minimum’ level of asset condition (i.e. that results in safe operation of the network at established asset failure rates) with ‘Do Something’ improved condition options. ‘Do Something’ options may include enhanced renewals regime or greater maintenance or operational expenditure.
- Where costs and benefits can be monetised, Cost Benefit Analysis should assess the Whole Life Costs (i.e. both capital and operational expenditures) against Whole Life Benefits (for example; reduced user journey time delays from optimised maintenance regimes or lower vehicle operating costs from smoother road surfaces).
- Appraisal may indicate that options to improve asset condition, involving improved resilience standards, may be higher VfM than existing ‘Do Minimum’ asset condition levels. For example, because higher levels of upfront spend help to avoid later road closures because of more frequent maintenance works. Equally, appraisal may indicate that improvement options result in unnecessary gold-plating.
- This approach is consistent with National Highways (2017) Asset Condition Modelling for RP2 and DfT’s Winter Resilience in Transport (2011) analyses. Argyroudis (2021) shows how “breakeven rules” can be applied in this analysis to inform the design thresholds for acceptable levels of asset condition (e.g. “maximum risk tolerances” or “viable minimum service levels”).

4.5 Outstanding Considerations

4.5.1 Outstanding Appraisal Challenges

Appraising resilience in a transport context based on an expected value avoided loss framework faces several outstanding analytical challenges. These challenges arise because resilience deals with uncertainty, dynamic behaviours, and systemic interactions that existing models deployed in transport appraisal struggle to capture. Recognising these challenges is a critical precursor for developing a fully comprehensive approach to appraising resilience in TAG.

Precise Operational Definitions of Resilience

A pragmatic and conservative approach has been proposed for defining the scope of resilience appraisal in operational terms. A default value is that resilience considers shocks that last over six hours in duration, based on existing transport model parameters and analysis of real-world shock events. However, relevant risk thresholds and metrics differ significantly across transport modes and transport bodies have yet to adopt specific definitions. Extensive transport modelling or data analysis would be required to ascertain robust threshold values across modes.

Data on risk probabilities

While the expected value framework is a powerful tool, it relies on accurate probability estimates of future risks, which are often unavailable or highly uncertain for resilience planning. Risks may change in frequency, intensity and form over time. The RGC Resilience Guide (Aven et al. 2018) explains that risk assessments struggle to produce reliable probability estimates when there is large uncertainty about what types of events may occur. The presence of chronic risks such as changing weather patterns due to climate change may amplify this uncertainty, making historical data unreliable for future risk probabilities.

Limitations of existing transport models

Existing transport models that are calibrated using such historic data risk introducing ‘fat-tailed risks’ – rare but catastrophic events, which are poorly represented in average-based models. These models are typically calibrated for day-to-day conditions and assume short-term elasticities. They rarely capture

prolonged disruptions or network degradation, meaning welfare losses from unanticipated long-duration shocks are underestimated

Extrapolating welfare losses from transport models based on existing valuation parameters for day-to-day conditions are likely poor proxies for the welfare losses associated with unanticipated long-duration shocks. Hurst, M. (2021) argues that conventional expected value approaches fail under fat-tailed distributions, where rare catastrophic events dominate risk profiles.

Existing transport models often also assume that travel demand and route choices revert to a new equilibrium after perturbations. However, travel patterns can reorganise after major shocks (Larcom et al, 2017) based on new behavioural responses resulting in new equilibrium conditions.

Complex, cascading and inter-dependent risks

Impacts from acute shocks occur at different layers of the transport system, compound through time and often interact with other infrastructure systems such as energy and digital systems. The UN Analytical Framework on Risk and Resilience (2017) emphasises that systemic risks are dynamic and interdependent, so historical data cannot reliably predict future disruptions. It is difficult to estimate losses across different systems which each requires specialist knowledge and appraisal experience. The European Commission JRC (2024) Resilience Assessment for Critical Infrastructure also notes cascading failures make appraisal highly complex.

Isolating the resilience benefit in the presence of additional trip-making

Some interventions that may have improved resilience based on existing demand conditions, may lead to offsetting effects. For example, large capacity enhancements such as the Lower Thames Crossing can lead to additional demand for journeys and new trips which, over time, may erode the spare capacity that confers greater resilience during acute risks. Analysing all these loss impacts can be complex and time-consuming.

Time inconsistency in stated preference methods

Individuals may value their time higher during unanticipated shocks which often lead to significant opportunity costs. Past experience with disruptions may also lead to different values of time across transport users. For example, Strack & Taubinsky (2024) show how preferences change after shocks, creating bias in ex-ante stated preference valuations. Stated preference surveys that inform current values of time may therefore understate disruption costs because respondents rarely anticipate extreme shocks.

Insurance value of resilience

The conceptual framework does not currently consider the potential “insurance value” of resilience. This means the additional benefit individuals derive from reducing uncertainty and gaining peace of mind that severe disruptions are less likely to occur. Tonn et al. (2018) explain how traditional reliability analysis underestimates the “peace of mind” and uncertainty-reduction benefits of resilience. Whilst insurance value is similar to the concept of option value articulated in TAG the critical difference is that the former is rooted in risk aversion and variance reduction, whilst the latter is rooted in uncertainty about future personal use.

Presentation of Welfare and GVA Based Impacts

DfT (2019b) demonstrated how welfare and GVA based forms of appraisal capture distinct impacts that can be robustly reconciled only through detailed analysis. Wider economy modelling approaches that are required to estimate ‘Indirect’ supply chain impacts and wider GDP impacts typically produce outputs in ‘GVA’ terms, that need to be reconciled with other ‘standardised’ impact estimations calculated in ‘Welfare’ terms. This could lead to substantive analytical effort.

Proportionality

The complex data and analytical requirements to fully appraise resilience using monetised analysis may only be feasible for a limited number of major infrastructure schemes. A qualitative approach has been suggested as part of the conceptual framework however this provides limited information around the size of the potential impact. An alternative approach of providing quantitative look-up values for analysts to deploy efficiently in their appraisals is possible and the research required to enable such an approach is defined in Section 4.5.2.

Project-level and Programmatic appraisal.

Project-level appraisal may fail to capture system-wide interdependencies and cascading benefits of resilience interventions that become visible only at programme or portfolio level (ITF, 2024). Where resilience is a programme-level objective, programmatic appraisal may be able to better weigh the full range of resilience options against each other and to accurately analyse the system-wide interdependencies and cascading factors that exist. For example, resilient interventions that do not represent Value for Money when examined individually within a dozen different road schemes in a region, may represent Value for Money when analysed as a regional programme of investment – due to the interdependencies and potential for cascading failures within the regional transport system. programmatic appraisal however adds greater analytical complexity for analysts.

4.5.2 Recommended Approaches for Overcoming Appraisal Challenges

New research developing look-up tables for resilience appraisal values

Development of proportionate resilience appraisal guidance requires more detailed analytical studies to further quantify both the operational definition of resilience across transport modes, and the losses which typically occur from these incidents. The existing literature provides a large range of such values and a bespoke exercise is required. This should take the form of seeking to develop **look-up tables of resilience appraisal values** which codify the relationship between acute shocks of specific thresholds and expected losses in the resilience impact categories. Such an exercise could undertake a data-led or model-led approaches:

- A **data-led approach** is key for grounding resilience appraisal in available evidence. Disruption data, including cause, frequency, location, or duration at different spatial locations across transport networks, could be combined with data about normal traffic volumes and the presence of alternative routes at these locations. This could be used to build tables of expected disruption events and the expected scale of their direct transport user impacts. For example, this could draw on analysis of National Highways incident and traffic data.
- A **transport model-led approach** could replicate and analyse disruption scenarios using transport models. Transport models would be run to simulate both historic and theoretical future events would the expected duration of disruption events and the expected scale of their direct transport user impacts could be estimated.
- An **economic model-led approach** could model the same disruption scenarios used in the transport model-led approach but using wider economic models. I-O or CGE models would be run to simulate both historic and theoretical future events would the expected duration of disruption events and the expected scale of their indirect supply chain and wider economy impacts could be estimated. In line with Section 4.4.2 given the significant issues around displacement with I-O modelling, these results should be carefully interpreted and explicit additionality adjustments should be made to better capture the “net” impacts.

From data and modelling-led approaches, look-up tables of monetised benefits could be developed based on TAG appraisal parameters such as values of time. When combined with scheme specific data on traffic volumes, this approach could provide a monetised valuation of resilience for use in TAG appraisals. This modelling could also distinguish threshold levels and expected values across modes. In particular, illuminating the differences between rail and road valuations – reflecting nuances in how transport modelling tools appraise journey time impacts across scheduled and unscheduled journey types.

Exploration of total value systems approaches

As described in Section 4.4.2, strategic-level modelling approaches such as **total value systems** should also be considered. These approaches have the benefit of capturing systemic value – where resilience could be employed to protect the transport systems that deliver Direct Transport User Benefits, Wider Economic Impacts and other impacts and seek to optimise this value within a changing context. Total value systems have been recommended to analyse the value of energy security in a NATO context (Field et al, 2024) and a feasibility study should be undertaken to examine the potential application to the transport system. Such an exercise would build on **transport ‘digital twins’**, such as the DfT Integrated Network Management Digital Twin (2024), which codified many of these interdependencies in the

transport system. Application of these models could also have the wider benefit of providing more readily accessible measures of performance to better inform thresholds for undertaking resilience appraisal (see Section 4.2.3).

Values of time in acute shocks

Section 4.4.2 described how congestion multipliers have been estimated for heavy and light congestion conditions, reflecting the rising disutility of time for transport users as they lose flexibility to reschedule their journeys and activities, and due to the stress and unpredictability involved. Further research could look at how users respond to major acute shocks (e.g. in scenarios of delays of more than six hours) and examine the evolution of the perceived cost of travel time across higher delay scenarios for use in resilience appraisal.

This work should be founded on a literature review that extends beyond mainstream studies and captures evidence from non-linear value of time studies, risk aversion evidence, behavioural economics and insurance valuation. Hypotheses should be developed that can be tested using revealed or stated preference approaches. Stated preference design should consider scenario-based framing, a broader set of attributes than traditional studies and non-linear utility specifications. This could also be augmented through revealed preference approaches such as analysing post-incident data and identifying other potential natural experiments.

5 Recommendations for incorporating appraisal of resilience into TAG

This chapter builds on the conceptual framework presented in Chapter 4 – identifying the key recommendations for how the appraisal of resilience should be incorporated into DfT's Transport Analysis Guidance (TAG). The chapter highlights the key implications of the conceptual framework, sets out a proposed TAG structure for taking forward the framework and summarises the key aspects of guidance that should be contained within this. The next steps for developing TAG guidance are identified, and required new areas of research highlighted. Interactions with other aspects of TAG are considered, and three case studies representing example applications of this guidance are presented. This chapter should be read in conjunction with Chapter 4.

5.1 Implications of the Conceptual Framework for TAG

The conceptual framework concluded that resilience is a distinct impact category to other impacts already appraised in TAG (option value, reliability etc). However, it also concluded that resilience is measured through calculating the welfare losses avoided based on existing TAG impacts. Existing transport and economic modelling tools used in TAG are not currently configured to calculate the welfare impacts from 'low-probability, high-impact' shock incidents in the tails of a normalised distribution of incidents. This presents a key choice for TAG: to deliver significant changes to existing transport modelling tools – or to create bespoke standalone guidance for resilience appraisal. The former would involve a review and update across TAG Units, whilst the latter could be formalised in a new TAG Unit. This review recommends a two fold-approach:

TAG Recommendation 1: Creating a new TAG Unit to represent a 'one stop shop' for consistent guidance relating to the appraisal of resilience.²⁷

TAG Recommendation 2: Conducting new research to upgrade transport modelling tools, and developing new modelling approaches such as digital twins and systems resilience models.

A potential structure for this guidance is set out in Section 5.2, alongside recommendations on how the appraisal results of resilience appraisal should be reported. Overall, given its exploratory and innovative nature resilience impacts should either be reported as a:

- **Level 3 Indicative Impact** if a monetised assessment has taken place, in line with DfT's Value for Money Framework; or
- **Non-monetised impact** in Appraisal Summary Table if a non-monetised assessment has taken place, in line with TAG Unit A4.1

5.2 Recommendations for new TAG Unit and further research

Table 16, below, sets out a proposed TAG structure for taking forward the conceptual framework and summarises the key aspects of guidance that should be contained within this. The next steps for developing TAG guidance are also identified, with required key areas of research highlighted in blue. Acknowledging the additional analytical demands that following the full monetised approach would place on affected schemes, research should focus on producing practical tools such as quantitative look-up tables that can be applied more readily than fully bespoke analysis. Guidance can start by emphasising the non-monetised approach and be built up over time as the evidence base becomes more mature.

²⁷ An alternative approach would be to integrate resilience impacts into TAG Units A1.3 and A2.1 however this may not fully pick up all relevant appraisal dimensions.

Table 16. Summary outline of recommendations for a new TAG chapter.

Proposed TAG Unit chapter	Proposed chapter guidance	Next step / further research required
1.1. Strategic assessment – applicability	Determine applicability of resilience appraisal: <ul style="list-style-type: none"> • Use Resilience Four Questions to identify how resilience interacts with case for change • If resilience is material to the case for change, codify in Strategic Objectives • If resilience features as a Strategic Objective, or is a material consequential impact, TAG Resilience Unit guidance should be followed 	Further policy analysis to define precise decision tree
1.2. Strategic assessment – proportionality	If resilience appraisal is applicable, determine proportional appraisal approach. For example: <ul style="list-style-type: none"> • Resilience is a primary objective or resilience impacts potentially large – undertake monetised economic assessment • Resilience is a secondary objective or resilience impacts potentially minor or moderate – undertake non-monetised assessment 	Further policy analysis to define precise proportionality test
1.3. Strategic assessment – resilience strategies	Consider whether a portfolio, programmatic or project-level appraisal is most appropriate.	Further policy analysis to define decision rules
	Consider any resilience strategies and options that should feature in the economic appraisal: <ul style="list-style-type: none"> • Check long-list and short-list appropriately capture resilience options • Check these cover the relevant aspects of the ‘resilience cycle’ 	Further policy analysis to define comprehensive list of resilience options in transport
2.1 Economic assessment – monetised avoided welfare loss	Determine geographic boundary for the appraisal: <ul style="list-style-type: none"> • Undertake high-level network analysis • Identify the critical points on the transport network where acute shocks are expected to have largest impact • Determine whether route or network resilience to be appraised (or both) 	Exemplify through case studies
	Parameterise the acute shock(s) to be modelled: <ul style="list-style-type: none"> • Select type and number of shocks • Quantify length of delay • Determine temporal features (time of day, seasonal effect) 	Exemplify through case studies Consider development of stylised analytical scenarios
	Determine probability of the shock occurring over the appraisal period in the Do Nothing and Do Something option(s): <ul style="list-style-type: none"> • Review historic time-series data on incident delays of > 6 hours in duration 	Collate mode and link specific incident duration data and make accessible Exemplify through case studies Further research: quantitative research to

	<ul style="list-style-type: none"> • Collate evidence on whether probability of delays over six hours is materially different across Do Nothing and Do Something options • Estimate probability change. Where evidence is not robust, an unchanged probability should be assumed 	estimate mode-specific incident delay thresholds / other threshold types
	<p>Determine the impact changes to be assessed in the Do Nothing and Do Something option(s):</p> <ul style="list-style-type: none"> • Transport user impacts (e.g. changes in journey times, vehicle operating costs etc.) • Wider economic impacts (e.g. changes in value-added) 	Further analysis to define proportionality tests and/or decision rules.
	<p>Appraise changes in transport user impacts over the appraisal period in the Do Nothing and Do Something options:</p> <ul style="list-style-type: none"> • Refer to look-up tables to provide high-level estimate of potential transport user impact losses • If proportional, run transport models to quantify changes in transport speed and flows following the shock • Estimate the resultant change in transport user journey times and vehicle operating costs (using software such as TUBA) • Apply any additional uplifts to account for presence of imperfect competition 	<p>Further research: Create look-up tables (e.g. linking disruption data to generalised scale of transport user impacts)</p> <p>Further research: mode-specific guidance for bespoke modelling</p> <p>Further research: examine use of digital twins for modelling impacts</p>
	<p>If proportional, appraise changes in wider economic impacts over the appraisal period in the Do Nothing and Do Something options:</p> <ul style="list-style-type: none"> • Refer to look-up tables to provide high-level estimate of potential value-added loss • If proportional, consider bespoke input-output modelling exercises 	<p>Further research: Create look-up tables (e.g. linking disruption data to generalised scale of value-added losses)</p> <p>Further research: examine use of digital twins for modelling impacts</p>
	Use standardised values of time in the monetised assessment	Further research: Examine how users respond to major shocks and impact on perceived cost of travel time
	<p>Given their exploratory nature, report both transport user and wider economic impacts as a Level 3 Indicative Impact in line with DfT's VfM Framework.</p> <p>For transport user impacts, wider appraisal metrics (NPSV, BCRs) containing Level 3 impacts should be calculated and reported supplementary to core appraisal metrics</p> <p>For GVA-based wider economic impacts, these should be reported separately to welfare-based appraisal metrics.</p>	Exemplify through case studies

2.2 Economic assessment – non-monetised avoided welfare loss	Review proposed non-monetised assessment framework and suggested sub-factors and determine whether any adaptations are required (e.g. for bespoke resilience impacts)	Exemplify through case studies
	For the Do Something option(s) over the appraisal period, conduct Impact Directionality assessment: beneficial, neutral or adverse	Further research: Following look-up value research, review whether greater quantification could be added to define thresholds in the qualitative framework
	For the Do Something option(s) over the appraisal period, conduct Impact Size assessment: slight, moderate or large	
	Report as a non-monetised impact category in Appraisal Summary Table, in line with TAG Unit A4.1 Social Impact Appraisal.	Exemplify through case studies
2.3 Economic assessment – chronic risks	Identify relevant chronic risks and determine the extent to which the relationship between acute and chronic risks are known and can be robustly analysed	Exemplify through case studies
	<p>If the relationship between acute and chronic risks is known and can be robustly analysed, the assessment of acute risks should be adjusted to incorporate the impact of chronic risks:</p> <ul style="list-style-type: none"> • For monetised assessment: adjust annual welfare changes prior/post shock, severity of shock, probability of shock etc. • For non-monetised assessment: adjust directional impact and size impact scoring 	Exemplify through case studies
	<p>If the relationship between acute and chronic risks is not known, consider appraisal through a 'resilience standards' approach:</p> <ul style="list-style-type: none"> • Appraise different levels of asset condition implied by alternative resilience standards • Use CBA to appraise whole life costs (capex and opex) and transport user impacts 	Exemplify through case studies
4.1 Risk and uncertainty assessment	<p>If monetised assessment has been undertaken, calculate a probability switching value:</p> <ul style="list-style-type: none"> • The risk that the decision-maker would need to believe for the intervention to represent a minimum desired level of VfM • Calculate either based on (1) resilience improvement considered in isolation or (2) resilience improvement considered as part of wider transport scheme 	Exemplify through case studies
	<p>Consider application of supplementary 'decision making under uncertainty' techniques:</p> <ul style="list-style-type: none"> • Adaptive pathways, Real options analysis, alternative decision rules, portfolio analysis • Particularly relevant when risks are complex, multi-dimensional or highly dynamic in nature 	<p>Further analysis to define decision trees and/or decision rules.</p> <p>Exemplify through case studies</p>

	<p>Clearly report risk information in the VfM assessment:</p> <ul style="list-style-type: none"> • Communicate probabilities and probability switching values prominently, on parity with other key appraisal metrics (NPSV, BCR etc.) • Accompany with a risk narrative, clearly articulating maturity of evidence and any key assumptions or uncertainties • Citing underlying evidence sources 	Exemplify through case studies
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5.3 Wider TAG implications of a new TAG Unit

Developing a new TAG Unit in line with Section 5.2 is expected to have wider implications for other Units to ensure consistency across TAG. For example, it is recommended that:

- **DfT Value for Money Framework** – resilience impacts should be added to the types of impact that may be relevant to transport appraisal.
- **TAG Unit A1.1 Cost Benefit Analysis** – principles should be built on the reference the need for supplementary appraisal to capture resilience impacts beyond existing modelling tools.
- **TAG Unit A1.3 User and Provider Impacts** – in relation to reliability appraisal, should note the six hour incident delay distinction between reliability and resilience impacts.
- **TAG Unit M4 Forecasting and Uncertainty** – should recognise the need for potentially supplementary risk and uncertainty assessment where resilience impacts have been reported.
- **TAG Unit A2.1 Wider Economic Impacts** – should include short-run value-added loss impacts for businesses using the transport network and the supply chain as a Level 3 Indicative Impact.
- **TAG Unit A4.1 Social Impact Appraisal** – should note the potential for resilience appraisal to be added to the list of non-monetised impacts within the Appraisal Summary Table (AST).
- **TAG Unit 4.3 Place-Based Analysis** – should note the potential to map resilience impacts spatially (e.g. showing distributional considerations around route and network resilience)

These TAG Units should be surgically updated to cite the interaction with resilience impacts and include cross-references to the standalone Resilience Appraisal TAG Unit for more detailed guidance.

5.4 Case studies

Chapter 2 and Chapter 3 highlighted a range of practical examples of resilience appraisal in action. Whilst none of these examples fully demonstrate the TAG guidance structure set out in Section 5.2, a relevant practical example of discrete economic assessment aspects of this framework is presented in the case studies below: Lower Thames Crossing and Dawlish Exeter to Newton Abbot. Given the limited best practice evidence, it is recommended that in development of the TAG guidance, DfT should work closely with transport bodies to identify specific live transport schemes that could represent ‘worked examples’ in this guidance.

Case Study: Lower Thames Crossing (2022)

Form of appraisal: Economic assessment – non-monetised (Recommended TAG Section 2.2)

Impacts captured: Direct transport user impacts

Appraisal context: The assessment appraised how LTC could help mitigate the impact from disruptive incidents at the existing Dartford Crossing that last longer than six hours – both the ability of LTC to reduce the probability of these incidents occurring, and to better manage recover from long duration impacts when they do occur. The assessment considered the whole Lower Thames Area, recognising the competing effects from journeys on the existing network experiencing lower losses, and new trip making over LTC now incurring losses. *Appraisal approach:* A non-monetised appraisal was developed based on four types of resilience:

- *Event resilience:* Appraising LTC’s ability to reduce adverse impacts associated with traffic accidents or disruptions lasting more than six hours

- *Weather resilience*: Appraising LTC's ability to provide a reliable crossing option for high-sided vehicles during high winds
- *Asset management resilience*: Appraising LTC's ability to reduce road user disruption from a more optimised maintenance regime at Dartford Crossing
- *Full closure resilience*: Appraising LTC's ability to preserve trip making across the Thames to the East in case of a catastrophic closure of the Dartford Crossing.

Appraisal findings: Overall, LTC was expected to deliver a **positive resilience impact**. An increase in resilience was assessed for each type of resilience impact:

- *Event resilience*: LTC expected to result in fewer incidents across the Lower Thames area, enable the network to recover more quickly from incidents and provide a partial diversionary route if incidents occur on the Dartford Crossing.
- *Weather resilience*: During periods of high winds which can close the QEII Bridge, LTC provides road users a more weather resilient alternative route than the Dartford Crossing.
- *Asset management resilience*: LTC enables the maintenance regime for Dartford Crossing to be optimised and less road users being impacted by major renewal work at Dartford Crossing.
- *Full closure resilience*: In the event of a catastrophic closure of the Dartford Crossing, LTC preserves trip making across the Thames east of London without major diversions.

Only the impact directionality score was reported – not the impact size. There was significant uncertainty around the impact size – due to uncertainty of the magnitude of the diversionary and additional trip-making impacts.

Case Study: Exeter to Newton Abbot Resilience Study (2016)

Form of appraisal: Economic assessment – chronic risk assessment

Impacts captured: Whole life costs, Direct transport user impacts

Appraisal context: The Dawlish section of the Great Western Main Line running between Exeter St Davids and Newton Abbot is exposed to hazards such as coastal flooding and storm damage as a result of climate change. Following the 2014 Dawlish landslides, Network Rail commissioned a series of resilience studies to assess long-term options to mitigate ongoing infrastructure degradation. The Resilience Strategy aimed to identify interventions required to improve resilience along the route.

Appraisal approach: The study adopted a multi-criteria assessment framework that evaluated options against technical feasibility, safety, environmental impact, and whole-life cost. Within the economic appraisal, Network Rail utilised TAG to assess whole life costs (including avoidance of emergency repairs and ongoing maintenance spend) and whole life benefits (including avoided disruption costs for passengers and job creation during construction) across Do Minimum and Do Something options. The analysis was repeated across several scenarios reflecting alternative pathways for climate change chronic risks.

Appraisal findings: Over the 60-year appraisal period, Network Rail estimated a Net Present Value of £245m for the Resilience Strategy option over and above the Do Minimum option and a positive BCR of 2.0, in line with a High VfM category. Further sensitivity testing reinforced the positive public value to the UK when expanding the appraisal period to a 100-year horizon reflecting the long design life of the proposed interventions.

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Appendix A – Rapid evidence review methodology

This literature review was conducted using a structured and transparent approach to identify, evaluate, and synthesise existing research on the appraisal of resilience in transport systems. The methodology followed the principles of a Rapid Evidence Assessment (REA), designed to be implemented at a faster pace than a full systematic review while still maintaining rigour and transparency.

Purpose and Scope

The objective of this review was to examine how resilience is defined, appraised, and identify how it may be more systematically integrated into transport policy and investment decisions. The review focused on three thematic areas, agreed in the Inception Meeting between DfT and PA Consulting:

- **Transport resilience policy, strategy and risks:**
 - How is resilience best defined in the context of transport schemes?
 - How far are cross-government definitions appropriate?
 - What are the key strategic policy considerations for transport resilience that need to underpin the appraisal framework?
 - What are the most relevant and material acute and chronic risks that impact resilience in a transport context?
- **Existing transport resilience appraisal frameworks:**
 - What forms of resilience have been appraised (e.g. route and network resilience), what are the common dimensions and how do they differ?
 - How is resilience currently being appraised across transport modes (including in resilience interventions and setting resilience standards)?
 - What costs and benefits have been evidenced from improvements in resilience in a transport context?
 - How far do these overlap with existing impacts (e.g. reliability and option value)?
 - Are there any relevant alternatives to cost-benefit-analysis (e.g. resilience standards/cost effectiveness analysis or wider uncertainty toolkits)?
 - How is resilience being considered in reaching value-for-money conclusions and factored into decision-making on transport investment?
- **Methods for quantifying and valuing transport resilience impacts (to underpin the conceptual framework):**
 - Which resilience impacts have been appraised quantitatively, and which qualitatively?
 - How mature and robust are the quantification approaches?
 - How suitable are current economic valuation techniques?
 - What are the biggest analytical challenges (e.g. modelling, forecasting, counterfactual definition)?
 - What methods could be applied from developments in HM Treasury Green Book supplementary guidance?
 - What methods from other countries and sectors could be relevant?

The scope included academic literature, government reports, and grey literature published in English, with a focus on UK and international transport systems.

Search Strategy

A pragmatic and structured search strategy was adopted to ensure broad and relevant coverage of the literature, while remaining proportionate to the scope and timelines of a REA. This included:

- Sources consulted: A mix of academic databases (e.g. Google scholar, JSTOR) and grey literature repositories (e.g. UK government publications, think tanks and international transport bodies). Technical databases such as IEEE Xplore were considered only where relevant to infrastructure resilience technologies
- Search terms: Iterative combinations of keywords such as “transport resilience”, “resilience appraisal”, “infrastructure risk”, “cost-benefit analysis”, “uncertainty”, and “value for money” were used. Terms were refined based on initial scoping and relevance of results

- Search techniques: Boolean operators (e.g. AND, OR) and filters (e.g. date range, language) were applied where appropriate to focus results
- Screening: Titles and abstracts were reviewed for relevance, followed by full-text screening of selected sources. Inclusion was guided by relevance to the thematic areas and the quality of evidence.

Inclusion and Exclusion Criteria

To ensure relevance and quality, the following criteria were applied:

- **Inclusion criteria:**
 - Peer-reviewed articles, government publications and reputable grey literature - noting that some grey literature reports may require closer scrutiny before inclusion (see note on the AACODS framework below)
 - Publications from the past 15 years (with exceptions for seminal works)
 - Studies focused on transport systems or transferable appraisal methodologies
- **Exclusion criteria:**
 - Non-English language sources
 - Opinion pieces or non-substantiated commentary
 - Studies unrelated to resilience or transport appraisal.
- **Quality assessment of selected literature:** Given the rapid nature of this assessment, a proportionate, high-level appraisal was conducted to ensure the credibility and relevance of included sources. Peer-reviewed and government publications were assumed to meet minimum quality thresholds. Grey literature was assessed using a simplified AACODS framework, focusing on the following dimensions:
 - Authority - Is the author or organisation reputable and qualified in the field?
 - Accuracy - Is the information supported by evidence, references, or data?
 - Coverage - Does the source address the research questions or thematic areas?
 - Objectivity - Is the content balanced and free from overt bias or commercial interest?
 - Date - Is the publication recent enough to be relevant, or clearly marked as a seminal work?
 - Significance - Does the source contribute meaningfully to understanding resilience in transport?

Sources have been critically assessed for credibility, appropriateness and reliability of methodology and relevance, generating a 1-3 score for each and an aggregate judgement outlined in *Table 17*, below. Factors assessed include year of publication, authors' track records, affiliated institutions, clarity of communication, impact and alignment with other sources.

Table 17. Accelerated evidence review scoring criteria

Category	Description	Score
Credibility	Is the study coherent?	1-3
	Can findings be trusted?	
	Does the author consider the limitation of their study or provide alternative views?	
Methodology	Is the study peer-reviewed?	1-3
	Is the research design or methodology appropriate?	
	Is it replicable?	
Relevance	Does the study help to answer the research questions?	1-3
Overall judgment	What is the overall judgment, considering the above categories?	1-3

Sources were not excluded solely on quality grounds, but limitations were considered in the synthesis.

Synthesis of Findings

A narrative synthesis approach was used to identify:

- Common themes and patterns
- Areas of consensus and divergence
- Influential studies
- Evidence gaps.

Limitations

This review may be limited by:

- Potential publication bias (e.g., underreporting of negative findings)
- Exclusion of non-English sources
- Limited access to proprietary or unpublished data.

These limitations were mitigated through expert validation and triangulation of findings across multiple sources. Expert validation was conducted through review and consultation with subject matter experts at DfT, PA Consulting as well as our expert panel and academic partners.

Appendix B – Summary tables of resilience appraisals

Table 18. Economic appraisal of resilience in transport (not exhaustive). Source: Multiple sources.

Transport scheme	Appraisal approach	Benefits captured
Airports Commission Phase 2 Operational Risk Assessment	Scenario-based assessment of risk to airport operations against six shocks	<ul style="list-style-type: none"> Improved ability to prevent, absorb, adapt to, and recover from disruptive events such as flooding, power outages, fuel shortages, terrorism, extreme weather, and volcanic ash Identification and costing of additional mitigation strategies beyond core scheme designs Reduction of residual risk through strategic planning and mitigation measures Improved system-wide capability to manage multiple simultaneous risks Consideration of interdependencies with surrounding areas and industries to avoid worsening external impacts
Economic benefits of incident management (Environment Agency 2020)	Cost-benefit analysis	<ul style="list-style-type: none"> Quantified avoided damages Positive benefit-cost ratios Reduced environmental damage (e.g. water pollution) Avoided health risks and recreational losses. Reduced business disruption and infrastructure damage. Enhanced public trust and institutional reputation Improved future incident response through learning and partnerships
Exeter to Newton Abbot Geo-Environmental Resilience Study (Network Rail, 2016)	Multi-criteria assessment framework including Indicative capital costs and anticipated benefits	<ul style="list-style-type: none"> Reduced maintenance costs Avoidance of emergency repairs Job creation and local investment Amenity enhancement
ICARUS Project - European Road Authorities (2022)	CBA and multi-criteria analysis for climate adaptation	<ul style="list-style-type: none"> Long-term cost savings Improved decision-making under uncertainty Inclusion of co-benefits such as social equity
"Lack of Resilience in Transportation Networks: Economic Implications" Kurth, Kozlowski et al. (2020)	Scenario-based comparison	<ul style="list-style-type: none"> Avoided GDP Losses
Managing uncertainty in the second National Infrastructure Assessment (NIC, 2022)	Scenario-Based Planning, stress-testing	<ul style="list-style-type: none"> Improved value for money Reduced risk of underinvestment

Milan Malpensa Airport (Pagliara, F. and Zingone, M., 2023)	CBA focused on resilience to adverse weather events	<ul style="list-style-type: none"> • Reduced service disruption • Avoided economic losses • Enhanced safety and operational continuity
National Highways – Resilience Technical Annex	Scenario Analysis, A Regional Traffic Model (RTM), Transport User Benefit Appraisal (TUBA)	<ul style="list-style-type: none"> • Quantified benefits from reduced incident durations • Improved network recovery • Enhanced journey time reliability
"Resilience and Efficiency in Transportation Networks" Ganin et al. (2017)	Stress testing	<ul style="list-style-type: none"> • Quantified delay reductions • Identification of vulnerable and robust cities • Increased avoided costs
Rotterdam Port	Port Performance Indicators (PPI) Platform and Risk Mapping	<ul style="list-style-type: none"> • Enhanced operational continuity during supply chain shocks • Reduced downtime • Improved port competitiveness • Improved stakeholder coordination
"Winter Resilience in Transport: An Assessment of the Case for Additional Investment" (DfT, DECC, DEFRA, 2011)	Scenario-based cost-benefit analysis, national-level economic impact assessment	<ul style="list-style-type: none"> • Reduced disruption costs • Improved rail reliability • Enhanced local authority decision-making

Table 19. Performance indicator assessment of resilience in transport (not exhaustive). Source: Multiple sources.

Transport scheme	Resilience measurement approach	Benefits captured
ARUP/Rockefeller Foundation City Resilience Framework	Qualitative scoring framework	<ul style="list-style-type: none"> • Health and wellbeing of individuals • Infrastructure and environment • Economy and society • Leadership and strategy (knowledge)
National Surface Water Flood Management (SWFM)	Future Flood Explorer (FFE) modelling with cost-benefit optimisation	<ul style="list-style-type: none"> • Reduced flood risk • Wider benefits from SuDS (amenity, biodiversity, carbon) • Strategic investment planning
Rail Predictive Maintenance Programme	Quantitative resilience metrics using machine learning anomaly detection	<ul style="list-style-type: none"> • Reduced system failures • Improved asset longevity • Increased safety and operational continuity
Teesside International Airport	AI-enabled early warning and health screening systems	<ul style="list-style-type: none"> • Improved pandemic resilience through airborne virus detection • Enhanced passenger safety • Reduced transmission risk

Windward AI Integration (UK Maritime Sector)	Risk-based incident prediction using AI behavioural modelling	<ul style="list-style-type: none"> • Reduced organised crime risk • Improved cargo security • Enhanced situational awareness
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Table 20. Specific Cases of Transport Disruption and Economic Output or Value Added Loss

Event	Severity / Length	Transport Infrastructure	Type of Economic Loss	£ loss equivalent (2025 prices)
Flood events in Netherlands (Koks and Thissen, 2016)	6 months plus	Port and maritime network	Direct and Indirect GVA reduction in supply chain (IO analysis)	~£745m (for 1/1000 year flood event)
Maritime network blockage (Qu et al. 2024)	8 days	Maritime shipping routes	Direct and Indirect GVA reduction in supply chain (IO analysis)	~£300m
Suez Canal blockage (Tran et al., 2025)	6 days	Maritime channel	Ship-operational, environmental and inventory-carrying costs	~£67m
US highway closure due to flooding (Hu, 2008)	4 days	Highway freight corridor	Private operating costs, logistics and scheduling costs, indirect market costs	~£42m (Washington State Department of Transportation Freight Systems Division, 2008)
A591 Cumbria landslides (2015)	5 months	Rural road	Daily GVA reduction from tourism and hospitality in Lake District due to reduced connectivity, asset loss, recovery grants (multi-source, survey-based and sectoral estimation approach)	~£150 million
Dawlish rail collapse (2014)	8 weeks	Rail line	Direct and Indirect GVA loss from severed rail connectivity (IO analysis)	~£1 billion

Appendix C – Case Study Annex

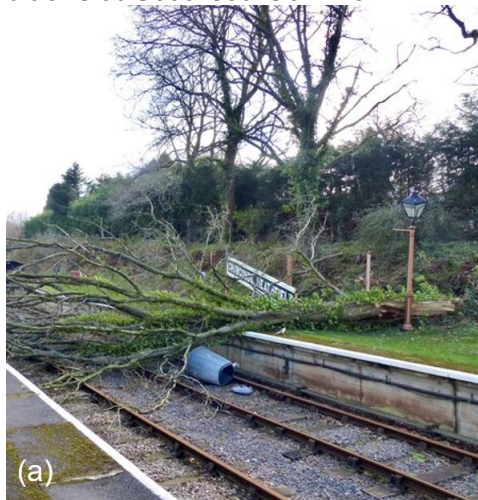
Case Study 22

Storm Eunice Disruption – February 2022

Storm Eunice struck the UK on February 18, 2022, bringing record-breaking wind gusts (up to 122 mph) and triggering a Red weather warning. It was one of the UK's most damaging storms since 2014 (Met Office, 2023). The storm caused widespread disruption across transport networks, including the suspension of all trains in Wales, closure of key bridges and motorways, and significant delays and diversions at major airports such as Heathrow. In total, 1.3 million homes initially lost power, and several fatalities and injuries occurred due to falling debris. Climate change intensified Storm Eunice by increasing moisture-driven diabatic processes (heat exchanges due to condensation and evaporation), which boosted vorticity (the storm's rotational strength), leading to stronger winds (Ermis et al, 2024).

Beyond immediate transport disruption, the storm triggered a cascade of secondary effects. Many people were unable to travel to work, leading to lost productivity. Schools were closed in affected areas, disrupting education and childcare arrangements. Emergency services and infrastructure operators faced prolonged recovery efforts due to extensive damage and hazardous conditions, with some areas experiencing days of service outages. UK insured losses were estimated to be between £200 and £360 million due to property damage, business interruption, and travel disruption from record-breaking winds and falling trees (Insurance Insider, 2022). These cascading impacts highlight the broader societal and economic vulnerabilities exposed by acute shocks as well as the importance of resilience planning in transport systems.

Image 14. Selected images showing storm Eunice disruption. (a) Felled tree at Crowcombe Heathfield station on The West Somerset Railway, (b) Damaged car at Bromley, (c) Treacherous driving conditions at Southsea Common.



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(b) [This photo](#) by Peter Trimming is licensed under [CC BY-SA 2.0](#).

(c) [This photo](#) by Tim Sheerman-Chase is licensed under [CC BY 2.0](#)

Source: [Storm Eunice: Record wind gust amid disruption - BBC News](#)

Appendix D – Accelerated evidence review scoring

Table 21. Accelerated evidence review scoring

Source title	Year	Type of source	Transport Resilience, Policy, Strategy, and Risks	Existing Transport Resilience Appraisal Frameworks	Credibility	Methodology	Relevance	Overall Judgement
Acemoglu and Tahbaz-Salehi	2025	Journal Article	✓		3	2	1	2
Ahmad and Al-Bazi	2023	Conference Paper		✓	2	1	3	2
Airport Operators Association (AOA)	2022	Industry Report	✓	✓	2	1	3	2
Airports Commission	2014	Government Report		✓	3	1	3	2
Airspace Change Organising Group (ACOG), and PA Consulting	2023	Industry/Consultancy Report		✓	3	1	3	2
Argyroudis	2021	Academic Report		✓	2	1	2	2
Arup and Rockefeller Foundation	2014	Professional/NGO Framework	✓		2	1	2	2
Atkins	2007	Industry Guidance Document	✓		2	1	2	2
Baldwin and Freeman	2022	Report/Guidance		✓	2	1	1	1
Bastiaanssen et al.	2022	Journal Article	✓		3	2	3	3
Bates et al.	2001	Journal Article	✓		3	2	2	2

Batley and Ibáñez	2013	Journal Article	✓		3	2	2	2
Batley et al.	2017	Journal Article		✓	3	2	1	2
Beiler	2016	Journal Article	✓	✓	3	2	3	3
Béné	2013	Academic Working Paper	✓		2	1	2	2
Bergantino et al.	2024	Journal Article	✓		3	2	2	2
Betts and Brown	2021	Government Committee Report	✓		2	1	2	2
Bhavathrathan and Patil	2015	Journal Article	✓		3	2	2	2
Bondemark et al.	2021	Journal Article	✓		3	2	2	2
Brand and Price	2005	Government Research Report	✓	✓	2	2	2	2
Biringer et al.	2013	Textbook/Academic Book	✓		3	1	2	2
Brunson & Norman	2024	Conference Paper		✓	2	2	3	2
Buckinghamshire Council	2025	Local Government Report	✓		3	1	2	2
Cabinet Office	2013	Government Report		✓	3	1	2	2
Cabinet Office	2023a	Government Policy Report		✓	3	1	2	2
Cabinet Office	2023b	Government Report	✓	✓	3	1	2	2

Cabinet Office	2025a	Government Report	✓	✓	3	1	2	2
Cabinet Office	2025b	Government Analytical Report		✓	3	2	2	2
Centre for Economic and Business Research	2014	Report/Guidance		✓	2	1	1	1
Chan and Schofer	2016	Journal Article	✓	✓	3	2	2	2
Chartered Institution of Highways & Transportation	2024	Professional Institution Report	✓		2	1	3	2
Choi et al.	2023	Journal Article	✓	✓	3	2	2	2
Civil Aviation Authority (CAA)	2014	Regulator Guidance Document	✓		3	1	3	2
Civil Aviation Authority (CAA)	2022	Regulator Guidance Document	✓		3	1	3	2
Civil Aviation Authority (CAA)	2023	Regulator Strategy Report	✓	✓	3	1	3	2
Civil Aviation Authority (CAA)	2024	Regulator Climate Adaptation Report	✓	✓	3	1	3	2
Civil Contingencies Act	2004	Legislation	✓	✓	3	1	2	2
Conference of European Directors of Roads (CEDR)	2022	European Industry Report	✓	✓	2	1	3	2

Cumbria County Council	2015	Local Government Multimedia Resource	✓		2	1	2	2
Davey et al.	2021	NGO/Industry Think Tank Report	✓	✓	2	1	2	2
Department for Business and Trade (DBT)	2022	Government Framework Report	✓	✓	2	1	2	2
Department for Business and Trade (DBT)	2024	Government Strategy Report	✓		2	1	2	2
Department for Business and Trade (DBT)	2025	Government Trade Strategy	✓	✓	2	1	2	2
Department for Environment, Food and Rural Affairs (Defra)	2016	Government Analytical Report	✓		3	2	2	2
Department for Environment, Food and Rural Affairs (Defra)	2025a	Government Climate Adaptation Report	✓	✓	2	1	2	2
Department for Environment, Food and Rural Affairs (Defra)	2025b	Government Analytical Guidance	✓	✓	3	2	2	2
Department for Environment, Food & Rural Affairs and Environment Agency	2023	Government/ Agency Report	✓		2	1	1	1

Department for Transport (DfT)	2014	Government Analytical Review	✓		3	1	3	2
Department for Transport (DfT)	2016a	Government Skills Strategy	✓		3	1	3	2
Department for Transport (DfT)	2016b	Government Guidance Document	✓	✓	2	1	3	2
Department for Transport (DfT)	2017	Government Framework Report	✓	✓	2	1	3	2
Department for Transport (DfT)	2018	Government Consultation Paper	✓	✓	3	1	3	2
Department for Transport (DfT)	2019a	Government/ Agency Report	✓	✓	2	1	2	2
Department for Transport (DfT)	2019b	Government/ Agency Report	✓	✓	3	1	2	2
Department for Transport (DfT)	2020	Government Analytical Overview	✓		3	1	3	2
Department for Transport (DfT)	2021	Government Analytical Guidance	✓		3	2	3	3
Department for Transport (DfT)	2022a	Government Strategy Report	✓		2	1	3	2
Department for Transport (DfT)	2022b	Government Guidance Document	✓		2	1	3	2

Department for Transport (DfT)	2024a	Government Analytical Consultation	✓	✓	3	1	3	2
Department for Transport (DfT)	2024b	Government Factsheet	✓	✓	3	1	3	2
Department for Transport (DfT)	2024c	Government Guidance Document	✓	✓	2	1	3	2
Department for Transport (DfT)	2025a	Government Guidance Document			2	1	3	2
Department for Transport (DfT)	2025b	Government Guidance Document	✓		2	1	3	2
Department for Transport (DfT)	2025c	Government Analytical Resource		✓	3	1	3	2
Department for Transport (DfT)	2025d	Government/ Maritime Strategy	✓		3	1	3	2
Department for Transport (DfT)	2026e	Government Integrated Transport Strategy	✓	✓	3	1	3	2
Department for Transport (DfT)	2025f	Government Investment Strategy			3	1	3	2
Department for Transport (DfT)	2025g	Government Guidance Document	✓		2	1	3	2

Department for Transport (DfT)	2025h	Government Data Book	✓	✓	3	3	3	3
Department for Transport (DfT)	2025i	Government Value for Money Framework	✓	✓	2	1	3	2
Department for Transport (DfT)	2025j	Government Guidance Document	✓		2	1	3	2
Department for Transport (DfT), Maritime and Coastguard Agency (MCA)	2025	Government Safety Code	✓		3	1	3	2
Department for Transport (DfT), Department of Energy and Climate Change (DECC) and Department for Environment, Food and Rural Affairs (Defra)	2011	Government Analytical Report	✓		3	2	3	3
East Sussex County Council	2025	Local Government Resilience Plan		✓	2	1	2	2
Eliasson et al.	2015	Journal Article		✓	3	2	2	2
Ermis et al.	2024	Journal Article		✓	3	2	2	2
European Committee for Standardization (CEN)	2021	Technical Standard/Guidance			3	1	2	2
European Environment Agency	2024	EU Agency Assessment Report		✓	3	2	2	2

Field	2016	Corporate/Industry Tool Guide		✓	2	1	2	2
Field et al.	2017	Blog/Online Article	✓	✓	1	1	2	1
Field and Look	2018	Journal Article			3	2	3	3
Field	2019	Industry Blog/Commentary		✓	1	1	2	1
Field	2020	Industry Magazine Article	✓		2	1	3	2
Field and Rodgers	2025	Magazine/Trade Journal Article	✓		2	2	3	2
Field et al.	2024	Industry Insight Article	✓	✓	1	1	2	1
Field	2025	Technical/Institutional Report	✓		2	1	1	1
Freeman, Groom, and Spackman	2018	Government Commissioned Report		✓	2	2	2	2
Frontier Economics	2024	Consultancy Analytical Report	✓	✓	3	2	2	2
Ganin et al.	2017	Journal Article		✓	3	2	2	2
Ge, Voß, and Xie	2022	Journal Article		✓	3	2	2	2
Gerges et al.	2022	Journal Article	✓	✓	3	2	2	2

Grey	2025	News Article			0	0	1	0
Guo et al.	2020	Journal Article			3	2	2	2
Gühnemann et al.	2012	Journal Article			3	2	2	2
Hallegatte	2019	Academic Working Paper	✓		2	2	1	2
Harrison	2022	News Article	✓		0	0	1	0
Harrison et al.	2019	Textbook/Academic Book	✓		3	1	2	2
Health and Safety Executive (HSE)	2020	Agency Analytical Report	✓		2	2	2	2
Health and Safety Executive (HSE)	2001	Agency Guidance Report			2	1	2	2
Heathrow Airport	2014	Operator Resilience Plan		✓	2	1	3	2
Heubaum et al.	2022	NGO/Think Tank Report	✓		2	1	1	1
Hill et al.	2025	Journal Article	✓		3	2	2	2
Hirsh	2021	Industry Blog/Commentary		✓	0	0	1	0
HM Government	2023	Government Review Report		✓	2	1	2	2
HM Government	2025	Government Risk Register		✓	2	1	2	2

HM Treasury	2024	Government Guidance	✓		2	1	2	2
HM Treasury	2025	Government Infrastructure Strategy	✓		2	1	2	2
HogoNext	2024	Corporate Blog Article	✓		0	0	1	0
Home Office	2018	Government Analytical Report	✓		3	2	2	2
Hu	2008	Doctoral Dissertation	✓		2	2	1	2
Inmarsat	2025	Industry Analytical Report	✓		2	2	2	2
International Association of Ports and Harbours (IAPH)	2021	Industry Association Guidance		✓	2	1	3	2
International Civil Aviation Organization (ICAO)	2025	Intergovernmental Report	✓		3	1	3	2
International Organization for Standardization (ISO)	2018	International Standard	✓	✓	3	1	2	2
International Organization for Standardization (ISO)	2021	International Standard	✓		3	1	2	2
International Organization for Standardization (ISO)	2024	International Standard	✓		3	1	2	2
International Transport Forum (ITF)	2021	Intergovernmental Forum Report	✓		3	1	3	2

International Transport Forum (ITF)	2022	Intergovernmental Forum Report	✓		3	1	3	2
International Transport Forum (ITF)	2023	Intergovernmental Outlook Report	✓		3	1	3	2
International Transport Forum (ITF)	2024	Intergovernmental/International Report	✓	✓	2	1	2	2
International Transport Forum (ITF)	2025	Intergovernmental Policy Report	✓	✓	3	1	3	2
Itani and Shalaby	2021	Journal Article	✓	✓	3	2	2	2
ITS Leeds	2025	Government Commissioned Study	✓	✓	3	2	2	2
Ivanov	2021	Journal Article	✓		3	2	2	2
Janić	2015	Journal Article		✓	3	2	2	2
JBA Consulting	2024	Consultancy Project Report			3	1	2	2
Johansson et al	2024	Conference Paper		✓	3	1	2	2
Kazmi et al.	2023	Journal Article		✓	3	2	2	2
Hill et al.	2025	Journal Article	✓	✓	3	2	2	2
Koks and Thissen	2016	Report/Guidance	✓		2	1	1	1
Kurth, Ali et al.	2020	Journal Article			3	2	2	2
Kurth, Ali et al.	2020	Journal Article			3	2	2	2

Laird et al.	2013	Conference Paper			2	1	2	2
Lin et al.	2024	Journal Article			3	2	2	2
Mansouri et al.	2009	Journal Article			3	2	2	2
Mattsson and Jenelius	2015	Journal Article		✓	3	2	2	2
Meaney et al.	2016	Conference Paper		✓	3	2	2	2
Met Office	2023	Agency Blog/Review Article		✓	3	1	2	2
Mohammed and Mandal	2023	Journal Article			3	2	1	2
Money et al.	2017	Government/ Agency Research Report	✓		2	2	2	2
Murray-Tuite	2006	Conference Paper		✓	2	1	2	2
Nair et al.	2010	Journal Article	✓		3	2	2	2
National Academies of Sciences, Engineering, and Medicine	2021	National Academy/Scientific Report		✓	3	1	2	2
National Highways	2022a	Government/ Agency Analytical Annex			3	1	3	2
National Highways	2022b	Government/ Agency Economic Report			3	2	3	3

National Highways	2023	Government/ Agency Technical Annex			3	2	3	3
National Highways	2024a	Government/ Agency Climate Change Report		✓	3	1	3	2
National Highways	2020	Government Agency Web Resource		✓	1	1	3	2
National Highways	2024b	Government/ Agency Climate Change Report		✓	3	1	3	2
National Highways	2025a	Government/ Agency Initial Report	✓		3	2	3	3
National Highways	2025b	Government/ Agency Guidance	✓		3	1	3	2
National Infrastructure Commission (NIC)	2020	Government/ Commission Analytical Report		✓	3	2	2	2
National Infrastructure Commission (NIC)	2022	Government/ Commission Analytical Report	✓		3	2	2	2
National Infrastructure Commission	2023	Government/ Commission Assessment	✓	✓	2	1	2	2

National Infrastructure Commission (NIC)	2024	Government/Commission Analytical Report	✓		3	2	2	2
Network Rail	2019	Operator/Industry Analytical Report	✓		2	2	3	2
Network Rail	2024	Operator/Industry Adaptation Report		✓	2	1	3	2
OECD DAC	1991	International Principles/Guidance	✓	✓	2	1	2	2
Office for National Statistics (ONS)	2020	Government Statistical Survey			2	3	2	2
Office of Rail and Road (ORR)	2025	Regulator/Agency Statistical Release	✓	✓	3	3	3	3
Onyeaunuforo et al.	2024	Journal Article			3	2	1	2
Pagliara and Zingone	2023	Journal Article		✓	3	2	2	2
Pogonyi et al.	2021	Journal Article	✓		3	2	2	2
Poo et al.	2024	Conference Paper	✓		2	1	2	2
Pregiolato and Dawson	2018	Journal Article		✓	3	2	2	2
Rail Delivery Group	2021	Industry/Trade Association Report	✓		2	1	3	2

Rail Delivery Group and PA Consulting	2025a	Industry/Consultancy Guidance Note	✓		3	1	3	2
Rail Delivery Group	2021	Industry/Trade Association Report		✓	2	1	3	2
Rail Delivery Group	2025	Industry/Trade Association Guidance	✓	✓	2	1	3	2
Rodin	2014	Think Tank/Book	✓		2	1	2	2
Rodrigue	2024	Textbook/Academic Book	✓		3	1	2	2
Rossa et al.	2024	Journal Article	✓		3	2	2	2
Royal Town Planning Institute	2021	Professional Institution Report	✓		2	1	2	2
Sayers et al.	2022	Consultancy Report	✓		2	1	2	2
Secure Power	2025	Corporate Blog Article	✓	✓	1	1	1	1
Serulle et al.	2011	Journal Article	✓		3	2	2	2
Simpson et al.	2021	Journal Article	✓		3	2	2	2
Smith & Tenekeci	2022	Conference Paper		✓	2	3	2	2
Steer Davies Gleave	2014	Consultancy Report		✓	3	1	2	2
Ta, Goodchild, and Pitera	2009	Journal Article		✓	3	2	2	2

Tidy	2025	News Article	✓	✓	0	0	1	0
Tran et al.	2025	Journal Article	✓	✓	3	2	2	2
Transport for London (TfL)	2023	Local Government/ Operator Adaptation Plan		✓	3	1	3	2
Transport Research Laboratory (TRL)	2018	Research Report		✓	3	2	2	2
UK Parliament	2020	Government/ Parliamentary Inquiry Report	✓	✓	3	1	2	2
UK Parliament	2025	Government/ Parliamentary Briefing	✓		3	1	2	2
United Nations Conference on Trade and Development (UNCTAD)	2022	UN Agency Guidance	✓	✓	3	1	2	2
Venables et al.	2014	Government/ Academic Appraisal Report	✓		2	1	2	2
Volden	2018	Journal Article	✓		3	2	2	2
Volpe National Transportation Systems Center	2025	US Government/ Agency Resource	✓	✓	2	1	3	2
Vugrin et al.	2011	Journal Article	✓	✓	3	2	2	2
Wardman et al.	2013	Journal Article	✓	✓	3	2	1	2

World Bank	2025	International Org/Agency Web Resource	✓	✓	2	1	2	1
World Economic Forum	2025	Think Tank/NGO Global Risks Report	✓		2	1	2	2
World Resources Institute	2019	NGO/Think Tank Report		✓	2	1	1	1
Xie et al.	2014	Journal Article	✓	✓	3	2	2	2
Yeomans	2025	Industry Blog/Comm entary	✓		1	0	2	1
Zhang et al.	2023	Journal Article	✓	✓	3	3	3	3



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Corporate Headquarters

10 Bressenden Place

London

SW1E 5DN

+44 20 7730 9000

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