Measuring Climate Resilience for Transport - Deliverable 1.1

Report addressed to The Department for Transport

April 2025

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Abbreviations

ADEPT	Association of Directors of Environment, Economy, Planning & Transport
ARP	Adaptation Reporting Power
BAG	British Aviation Group
CAA	Civil Aviation Authority
CAPEX	Capital Expenditure
CCA	Climate Change Act
CCAR	Climate Change Adaptation Report
CCC	Climate Change Committee
CCIA	Climate Change Impact Assessment
CCRA	Climate Change Risk Assessment
DARe Hub	Decarbonised, Adaptable and Resilient Transport Infrastructures
DEFRA	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
EA	Environment Agency
EWR	East West Rail
FOD	Foreign Object Debris
HS1	High Speed 1
HS2	High Speed 2
ICT	Information and Communication Technology
IDB	Inter-American Development Bank
ITF	International Transport Workers' Federation
MAG	Manchester Airports Group
NAP	National Adaptation Programme
NATS	National Air Traffic Services
NCA	National Climate Assessment
NIC	National Infrastructure Commission
NRW	Natural Resources Wales
OPEX	Operational Expenditure
ORR	Office of Rail and Road
RA	Risk Assessment
RQ	Research Question
RSSB	Rail Safety and Standards Board

SEPA	Scottish Environment Protection Agency
SRN	Strategic Road Network
TfGM	Transport for Greater Manchester
TfL	Transport for London
TfWM	Transport for West Midlands
UKRLG	UK Roads Leadership Group
WMCA	West Midlands Combined Authority
WS	Workstream

Definitions[1]

Asset criticality	Measure of the consequence of asset failure on an organisation
Asset Level Outcome	The impact of a hazard on a (transport) asset
Climate hazard	A climate-related physical event
Climate resilience	Ability of a system to anticipate, prepare for and respond to the impacts of climate change
Data	Information collected by transport organisations
Features of a resilient system	Processes, activities or outputs that can be used to indicate climate change resilience
Ideal metrics	Metrics identified at WS1 as optimal for the assessment of climate hazard impacts outcomes and system resilience
Incidence	The frequency or rate of occurrence of a climate hazard
Indicator	An observed value of a variable used to to signal a state
Interdependence	The dependence of two or more systems, modes or organisations on each other
Lagging metrics	A metric that offers insights into past results or performance
Leading metrics	A metric that offers insights into future results or performance
Magnitude	The size or extent of a climate hazard event
Metadata	Data that provides information about other data
Metric	A measure or indicator that is used to measure results or performance

[1] The definitions provided have been used within this project

Transport Mode	A subdivision of the transport sector with multiple organisations (e.g. aviation mode, rail mode)
Operational Level Outcome	The impact of a hazard on a (transport) system's operations
Priority hazards	Hazards identified as priorities for modes at WS1
Priority impacts	Impacts (asset level and operational) identified as priorities for modes at WS1
Service provision / Expected level of service	A measurable, defined target for the performance of a service
Threshold	A defined point past which there is a change (e.g in consequence severity, response action, etc.)

Executive summary

While there is considerable existing information available about how climate change impacts transport sector organisations and their individual networks, there is limited information available on how to measure these impacts over time at a transport mode (road, rail, aviation and maritime) or system level. This project aims to understand and collate the data that transport stakeholders capture on weather and climate related disruption and costs to improve understanding of the available data for measuring transport system resilience and adaptation. Ultimately, the project will support the monitoring and evaluation of the outcomes and impacts of DfT's climate policies. To address these requirements the project has been structured around three workstreams.

The objective of workstream 1 (WS1) was to review and summarise the evidence base for how the transport system is currently affected by weather and climate factors. Through desktop research and stakeholder engagement it aimed to understand the key hazards and impacted asset and operational outcomes to establish a potential set of ideal metrics to measure them. This report records the process, outputs and findings of the activities undertaken as part of WS1. Other reports will capture the processes, outputs and findings of workstream 2 (WS2) and workstream 3 (WS3).

The workstream identified:

- Priority hazards for each transport mode;
- How these hazards impact transport sector organisations, through the creation of impact chains;
- An initial set of metrics recovering the different links in the impact chains;
- Detailed findings from a desktop study and stakeholder engagement to consider further in workstreams 2 and 3.

Through this work, WS1 identified eight key points to be taken forwards to WS2 and WS3 and considered further:

- There are multiple aspects to climate resilience beyond just hazards and impact - For example: readiness, responsiveness, recovery & renewal. All aspects require consideration to ensure the comprehensive measurement of climate resilience of the transport system. This will be explored further in WS3.
- What makes each organisation in the transport sector resilient does not necessarily make the overall system or sector resilient. Climate resilience metrics at the organisational scale (or aggregates of those metrics) may not be suitable for measuring climate resilience at the sector level. This will be explored further in WS3.
- Metrics need a clearly defined purpose to provide value to their users. Metrics defined at the organisational level may only provide limited value at the system level, while metrics defined at the system level may only provide limited value to the organisations required to provide the necessary associated data. This will be explored further in WS3.
- Weather and climate attribution is a challenge for organisations due to data collection challenges and the inherent difficulty of separating weather and climate factors from other factors that result in the deterioration of performance or asset health. Data limitations may limit how climate resilience can be measured. This will be explored further in WS2.
- While metrics such as 'delays' or 'costs' are potentially useful climate resilience performance metrics, their definitions and underlying data vary across the sector. Common definitions and approaches to these metrics would support their use as a means of measuring climate resilience. This will be explored further in WS3.
- There is significant variation in resilience maturity across the transport sector and therefore large variations in the extent to which organisations across the sector have the capacity and capability to collect, compile and assess the data necessary to measure potential climate resilience metrics. This will be explored further in WS3.

- Interdependencies are a key aspect of transport system resilience and there is limited information available on them. A representative measurement of the transport system's climate resilience would benefit from an improved understanding of interdependencies. This will be explored further in WS3.
- Determining the expected service level for normal situations and under hazard conditions supports the definition of thresholds for what are 'acceptable' operational impacts. Organisations expressed their interest in understanding their stakeholders' expectations on performance in normal and hazard conditions so that they are better able to plan for the future. This will be explored further in WS3.

KPMG was a Subcontractor to Mott MacDonald for this study and contributed to stakeholder engagement to inform the research and analysis.

1 Introduction

1.1 Project and Workstream Background

1.1.1 Policy Background

Under the Climate Change Act (2008), the UK Government is required to assess the risks and opportunities posed by climate change, and how to best adapt to them. The act mandates the publication of a UK Climate Change Risk Assessment (CCRA) every five years, with an accompanying National Adaptation Programme (NAP) in response. The Climate Change Act also gives powers to the UK Government to request that certain organisations report on how they are adapting to climate change through the Adaptation Reporting Power (ARP).

Insights provided by ARPs as well as other publications including sector-specific and organisational reports and government publications are integral to the understanding of climate change effects, responses and the outcomes of policy across the transport sector. Within ARP reports, reporting organisations are required to lay out the current and projected effects of climate change on their organisation, as well as their plans for adapting to climate change. These reports are therefore crucial to the Government's ability to monitor the effects of weather and climate change as well as the effects of mitigation and adaptation policy on critical infrastructure.

DfT maintains numerous strategic priorities related to the Climate Change Act. Its focus is on delivering greener transport by tackling climate change, improving air quality by decarbonising transport, and managing the risks to, and opportunities for transport from climate change. In support of this DfT has developed a draft Transport Adaptation Strategy that was published in April 2024 and underwent consultation. It is currently undergoing a refresh following feedback and the July 2024 change in government[2].

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1.1.2 Project Objectives

This project will provide an understanding to the DfT of the data that transport stakeholders capture to measure the overall impacts of climate related costs, damage and disruption to the transport network. It looks to understand how to measure the impact of climate change on the transport system across the whole life cycle, and the sector's resilience and adaptation. Understanding the extent and quality of climate information and data repositories will act to inform monitoring and evaluation of the outcomes and impacts of policy and provide insight into areas of information deficit. While there is considerable existing information available about how climate change impacts transport sector organisations and their individual networks, there is limited information available on how to measure these impacts over time at a transport mode (road, rail, aviation and maritime) or system level. Addressing these requirements will support the monitoring and evaluation of the outcomes and impacts of DfT's climate policies.

1.1.3 Overview of Workstreams

To address the requirements described in section 1.1.2, the project has been broken down into three workstreams:

- **WS1:** Desktop study of key weather and climate risks to / impacts on the transport system.

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[2] This report was created in April 2025, and does not take into account any developments after that time period.

- **WS2:** Identifying existing data, metrics and indicators to measure key weather and climate risks to / impacts on the transport system, and
- **WS3:** Gap analysis & recommendations for addressing gaps.

1.1.4 Workstream 1 Purpose and initial approach

The objective of WS1 was to review and summarise the evidence base for how the transport system is currently affected by weather and climate factors. To address this brief, WS1 scrutinised sources from government, sector specific, organisational and international research groups, sectoral and policy bodies, and was directed by three research questions:

1. What are the key weather and climate risks which impact the transport system **(RQ1.1)** and what impact do they have **(RQ1.2)**?
2. What metrics should ideally be collected to assess these **(RQ2)**?

The information gathered through RQ1.1 and RQ1.2 allowed the prioritisation of hazards per transport mode, and the identification of their impacts. Hazard prioritisation through cross-report risk score assessment permitted insight into what stakeholders collectively perceive as their greatest climate hazards, and systems thinking mapping identified the chains between climate hazards and their impacts on assets and operations.

The information gathered through RQ2 aimed to determine potential metrics for measuring the priority hazards of each transport mode as well as how they affect assets and operations to improve understanding of the available data for measuring transport system resilience and adaptation. Desktop studies of stakeholder publications provided insight into the potential metrics which were tested with stakeholders through a cross-modal workshop.

The purpose of this report is to summarise the key findings from the WS1 desktop study and cross-modal stakeholder workshop, including the potential metrics. The outputs from Workstream 1 will be considered through activities being carried out in Workstreams 2 and 3. This report captures the outputs and findings of Workstream 1 only. Separate summary reports will capture the outputs and findings of Workstreams 2 and 3.

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1.1.5 Changes in Scope

While undertaking Workstream 1 several adjustments of activities were made to ensure that the work being carried out delivered the most useful outputs given the overarching project objectives. These have included: using a systems thinking based approach to develop Impact Chains for priority hazards and considering features of a resilient system as a means of measuring transport system resilience. Consideration of features of a resilient system allowed for other aspects of system resilience to be included in the scope of the project as well as hazards and impacts. These changes were made to deepen our understanding of the different metrics that would be needed to measure resilience of the transport system.

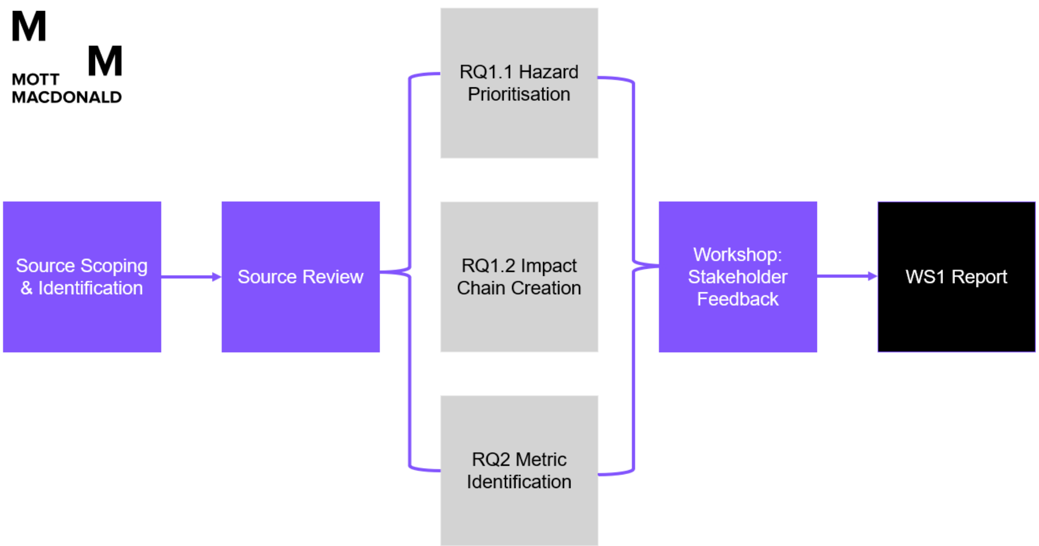
2 Methodology

2.1 Overview

Section 2 provides an overview of the methodology followed through WS1 (Figure 2.1). Workstream 1 was conducted as follows:

1. Source scoping, identification & review: An initial scoping and collection of sources of potential interest was conducted, with a specific focus on collecting ARP3 and 4 reports and CCRA 3 and 4 publications. Eighty-two publications were collected and reviewed, building evidence bases for RQ1.1, RQ1.2 and RQ2. Academic literature was assessed through reviews of CCRA4 literature yet not prioritised at WS1 due to the workstream's focus on organisational perspectives on their priority hazards and metrics to inform the creation of impact chains3.
2. Analysis of RQ1.1: Data was reviewed to understand the priority weather and climate hazards per transport mode.
3. Analysis of RQ1.2: Impact chains were created from priority weather and climate hazards to map how hazards lead to impacts on the transport modes.
4. Analysis of RQ2: Existing hazard and impact metrics identified from the source literature were reviewed to characterise the transport sector's practices and identify potential metrics.
5. Desktop study: Information captured through addressing the research questions was collected and synthesised to extract findings from the desktop study. These findings were taken forward and presented to stakeholders at the workshop.
6. Workshop: Stakeholders were engaged in a cross-modal workshop where findings from the desktop study were presented and critiqued.

Figure 2.1: High level overview of WS1



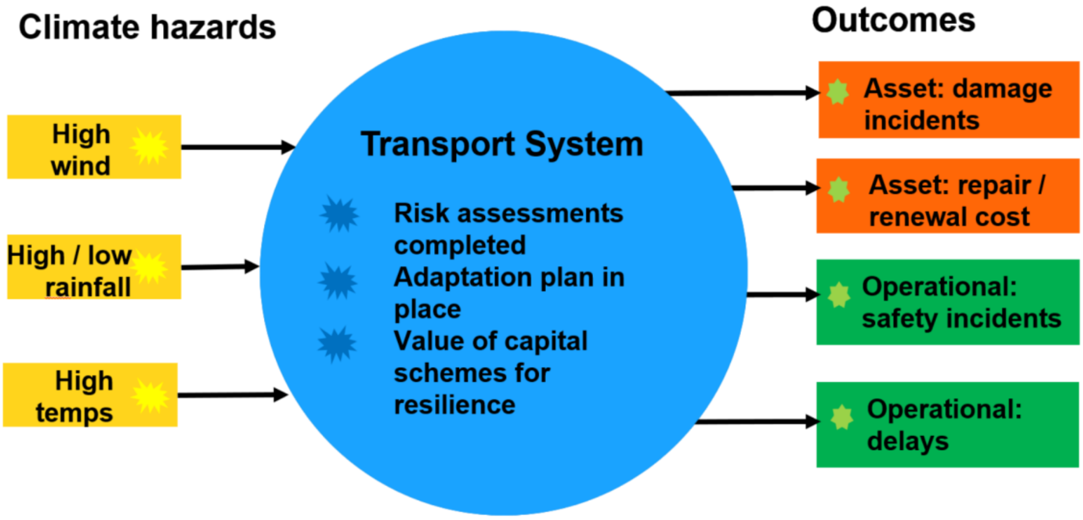
Source: Mott MacDonald, 2025

[3] Academic literature was assessed through reviews of sources such as CCRA4 reports which based their findings on academic literature.

2.2 Useful concepts

Figure 2.2 provides a visual representation of the systems-based approach taken to categorise and identify potential metrics. The approach considers measures of climate hazards, their impacts on transport systems and the resultant outcomes across asset-level and operational scales.

Figure 2.2: Conceptual diagram of systems-based approach



Source: Mott MacDonald, 2025

Within this project four transport modes have been considered: Road (including the strategic road network and local roads); Rail; Aviation; and Maritime. Some considerations have been across modes, reflecting that several stakeholders deliver transport services across multiple modes.

2.3 Desktop study

2.3.1 Identification of literature

The desktop study for WS1 reviewed 82 publications with a specific focus on ARP 3 and 4 reports and UK CCRA publications (list of sources in Appendix 1) as well as a review of the academic literature that has informed the UK's fourth Climate Change Risk Assessment (CCRA4). Some of the literature reviewed was published by organisations with cross-modal remits (e.g. Transport for London and Transport for the West Midlands). Additional literature including climate change adaptation reports (CCAR) annual reports and performance monitoring statements were reviewed, as well as international reports such as reports by the Inter-American Development Bank and International Transport Workers' Federation (ITF) to inform research on resilience and best practice. These data were used in analysis of priority hazards (RQ1.1), impact chain creation (RQ1.2) and identification and characterisation of metrics, following their sorting (RQ2).

2.4 Analysis of RQ1.1: Hazard Prioritisation

RQ1.1: *What are the key weather and climate risks which impact the transport system?*

To address the requirements of RQ1.1, the highest scoring climate risks and their scores were extracted from transport sector organisations' publicly available risk matrices and reports. No assessment of climate hazards or risks has been undertaken as part of WS1.

To identify the key weather and climate risks for each transport mode it was necessary to be able to compare and aggregate climate risk data for organisations. As each transport sector organisation's risk scores were based on their own internal scoring system, the comparison and aggregation was achieved by transforming each of their climate risk scores to a percentage.

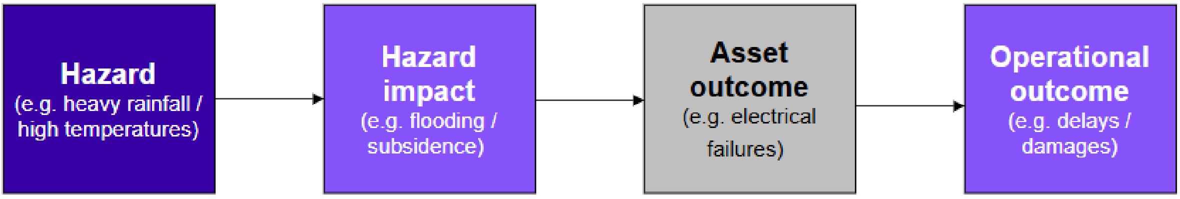
For example: An organisation using a 5x5 matrix to score their climate risks has a top risk score of 25. A climate risk scoring 25 for that organisation would receive a percentage score of 100%. Similarly, a second organisation using a 4x4 matrix to score their climate risks has a top risk score of 16. A climate risk scoring 16 for that second organisation would receive a percentage score of 100%. This approach allowed the risk scores of each organisation to be compared and aggregated. Where organisations used qualitative metric ranges, assumptions were made based on the information in their reports and the ranges used to transfer their climate risk scores to a percentage. For example, where a report scored a climate hazard as 'High' risk, the matrix scoring table was identified where available and the relevant numeric score was attributed to this hazard. Where no quantitative equivalents were provided, 'Low', 'Medium' and 'High' risk ratings were assigned risk score percentages of 25%, 50% and 75% to facilitate comparisons.

Once each organisation's climate risk scores were transferred to a percentage it was possible to identify the climate risks that were the most common and had the highest scores for each transport mode. This allowed the preliminary identification of the climate hazards which were most significant for each transport mode. This preliminary identification was then tested with transport sector stakeholders.

2.5 Analysis of RQ1.2: Impact Chain Creation

For each of the prioritised hazards, sector specific impact chains were developed. These chains organised individual events resulting from climate hazards in a chronological order, mapping the climatological event, its impacts on assets and resultant effects of those impacts on operational outcomes (as outlined in Figure 2.3). Where necessary, logical inferences were made to link impact chains together. Impact chains allowed for analysis of individual climate hazards and the extraction of their key impacts. A selection of impact chains was also mapped on the systems thinking tool, Kumu, facilitating analysis of links as a proof of concept (Appendix 4).

Figure 2.3: Hazard chain creation: Conceptual representation



Source: Mott MacDonald, 2025

2.6 Analysis of RQ2: Metric Identification

***RQ2:** What metrics should ideally be collected to assess priority climate hazards?*

Following the determination of priority climate hazards and impacts, existing metrics and data used to measure them were identified from the literature. Metrics were categorised into measures of hazards (e.g. precipitation rate), impacts on assets (e.g. repair cost) and impacts on operational level outcomes (e.g. delay minutes). Further subcategories were introduced to facilitate detailed sorting for hazard metrics (incidence, magnitude or threshold exceedance); asset level metrics (repair cost, asset condition or damage); operational level outcomes (operational cost, delay, safety, environment or revenue).

2.7 Stakeholder Engagement

Following the completion of the steps above, a 3.5-hour cross-modal workshop with attendees from 26 transport and regulatory organisations was held (full list in Appendix 3). Attendees were presented with a background to the project and its methodology, then provided with a summary of the key findings from the desktop study including priority hazards by transport mode, potential metrics for their measurement, potential metrics for impact measurement at an asset and organisational level and preliminary findings on the attributes of a resilient system. Feedback was then facilitated in groups, and key points were recorded on a collaborative Miro board and in group feedback sessions.

2.8 Assumptions and limitations

Whilst the methodology described above was developed to answer the WS1 research questions, there are some limitations:

- Scope and budget constraints limited the number of source materials the project team could review.
- As a desktop study was the first source of information, this results in several limitations including:
  - Inputs from smaller organisations such as local authorities and small ports that do not produce public reports were not able to be collected.
  - Locally significant hazards, impacts and data were not able to be identified as a result of the source documentation containing aggregate information at an organisational level.
  - Conducting hazard risk assessments was not an in-scope activity, meaning hazard prioritisation was informed by literature produced by sectoral bodies and specific asset owners only.
  - The effects of compound events on organisations was considered under-accounted for by stakeholders reviewing desktop study findings, due to the workstream’s focus on defining priority hazards.
- The information reviewed was mostly publicly available; commercially sensitive information has not been reviewed.

3 Desktop Study

3.1 Baseline

Given the project brief, a working assumption prior to the completion of the desktop study was that while transport organisations possess a good collective understanding of how climate change could impact transport performance through delays, damage and disruption, there is less information available to substantiate this or allow these impacts to be measured over time. Considering this, the literature reviewed for WS1 was expected to contain a good understanding of climate change hazards and their impacts but be sparsely populated with direct measures of the hazards, their impacts and outcomes. This section will present the metadata of organisations' climate hazard prioritisation and measurement.

3.2 Desktop study findings

3.2.1 Identification of hazards

Following the methodology detailed in Section 2, hazards were identified for each mode. The hazards identified are compiled in Table 1[4] below:

Table 1: Hazards identified by sector

Aviation	Maritime	Road	Rail
Precipitation / flooding (particularly intense rainfall / surface water flooding)	Precipitation / flooding (particularly intense rainfall / surface water flooding)	Precipitation / flooding (particularly intense rainfall / surface water flooding)	Precipitation / flooding (intense rainfall is a particular hazard for rail embankments)
High temperatures and heatwaves	High temperatures and heatwaves	High temperatures and heatwaves	High temperatures and heatwaves
Wind storms	Wind storms	Wind storms	Wind storms
Sea level rise and coastal flooding	Sea level rise, especially coastal flooding	Sea level rise, coastal flooding and coastal erosion	Sea level rise, coastal flooding and coastal erosion
Low temperatures	Low temperatures	Low temperatures	Low temperatures (freeze-thaw conditions and ice)
Snowfall	Snowfall	Snowfall	Snowfall
Drought	Drought	Drought	Drought
Wildfires	Wildfires	Wildfires	Wildfires
Electrical storms (lightning)	Ocean warming		Electrical storms (lightning)
Global wind patterns	Low river flow		
	Change in marine currents		

3.2.2 Priority hazards by sector (RQ1.1)

From the list displayed in section 3.2.1, hazard prioritisation was conducted for each transport mode individually. The lists were condensed to form shortlists of four priority hazards per sector for further

[4] This list of hazards is based off information collected from transport sector organisation's CCRAs. It is not the result of a CCRA carried out by this project.

analysis (Table 2). Four climate hazards were prioritised by their hazard scores for each mode as per the agreed project scope.

Table 2: Priority hazards by sector

Rank	Aviation	Maritime	Road	Rail
1	Precipitation / Flooding	Sea Level Rise	Precipitation / Flooding	Precipitation / Flooding
2	High Temperatures	Storms (storm surge / windspeed)	Storms (high windspeed)	Drought
3	Storms (high windspeed)	Precipitation / Flooding	High Temperatures	Storms (high windspeed)
4	Drought	High Temperatures	Drought	High Temperatures

Aviation: Literature reviewed for the aviation sector identified precipitation and flooding as the climate hazards posing the greatest risk. The 25 aviation literary sources generally considered the impact of heavy rainfall on surface water flooding and pollution risk due to overwhelming of drainage and surface runoff interceptor infrastructure. Groundwater, fluvial and pluvial flooding were also considered as risks to electrical equipment and airport buildings through potential damage from inundation and saturation.

High temperatures and drought were also identified as priority hazards, especially due to their impact on the health of passengers and staff, airport structures and electrical equipment, and due to increased fire risk associated with the ignition of aviation fuel and green infrastructure. Additionally, high temperatures were considered an operational threat to the aviation sector due to the effect of associated lower air densities, reducing lift for aircraft.

Finally, windstorms and high windspeeds were identified as priority hazards for the aviation sector due to their potential to damage airport structures, produce and transport foreign object debris (FOD), and disrupt aircraft and ground operations.

Maritime: Sea level rise was identified as the greatest climate hazard for the maritime sector, especially due to its potential to affect operational parameters (i.e. clearance under bridges and keel clearance due to changed hydrographic conditions). The 19 maritime reports reviewed also considered the impacts of more frequent coastal flooding, and disruption to aquatic environments by sedimentation.

Windstorms were considered by the sector as a risk due to storm surge, high windspeed, and changes in wind direction. Here, risks were considered for both port and vessel infrastructure where the risk of overtopping and vessel damage or capsize were scored as major risks.

Precipitation and flooding effects were considered to pose risks to port infrastructure through local inland flooding and inundation, as well as to aquatic habitats through the transport of pollutants through runoff.

Finally, impacts of increases in temperature were considered for all maritime asset classes. The stress impacts of high temperatures were considered on port structures and staff health, while the risks to vessels include navigational challenges due to lower river flow, decreased engine performance, and accelerated biofouling of ship structures associated with higher sea temperatures.

Road: The 8 road sector reports for the strategic road network scored hazards to their users and assets from precipitation and flooding as the most severe[5]. Precipitation and flooding risks focused on

[5] No information was sourced for local roads due to a lack of public reporting on climate adaptation or impact by local road operators.

a range of effects including the impact of road closures on users, and impact of scour, subsidence and material degradation on road assets.

Impacts from wind storms were identified by road sector reports to cause blockages of roads with debris, slope failures and the toppling of high-sided vehicles.

Impacts from high temperatures and drought were ranked as high risks for the road sector and focused mainly on direct impact on assets. Thermal expansion, road surface melting and subsidence of dehydrated substrata were discussed as significant associated risks to assets. Wildfire was also discussed by some organisational reports as a risk associated with drought and temperature increases, and the effects on both road assets through damage, and users through visibility constraints, safety risks, and disruption were noted.

Rail: The 15 source materials identified for the rail sector identified precipitation and flooding as priority hazards, principally through impacts on the degradation of track and trackside infrastructure. Flooding of tunnels, saturation of earthworks leading to an increase in slip risk, the impact of wet rails on train-track adhesion and resultant service disruptions were discussed as associated risks.

The hazards drought and high temperature were also identified as significant risks to rail infrastructure due to their potential to affect earthworks and track stability (drought) and track buckling (high temperatures). As well as these significant safety concerns, the impact of high temperatures was considered a health risk to passengers and staff on the network.

Finally, wind storms and high windspeeds were considered priority hazards due to their potential for damage to, and displacement of assets or vegetation that might block the track and create derailment hazards.

3.2.3 Impact chains (RQ1.2)

As detailed in section 2.5, impact chains were mapped for each of the prioritised hazards based on the literature review, to assess the impact of the priority climate hazards on asset damage and consequent delays. The full list of impact chains and their mapped use is contained in Appendix 2 and Appendix 4.

3.2.4 Potential metrics identified (RQ2)

The collection of metrics from source materials produced a longlist of measures and thresholds that organisations use to measure climate hazards and impacts. To better understand the metadata, identified metrics were categorised as per the metric categories and subcategories in Table 3. More information on the existing metrics and data being collected by organisations will be provided as part of Workstream 2.

Table 3: Metric categories and sub-categories

Metric Category	Definition
Hazard	Measures the extent (temporal / spatial) of climate hazards **(Subcategories:** *Incidence / Magnitude / Threshold exceedance)*
Asset level outcome	Measures the impact on transport assets of a hazard occurring **(Subcategories:** *Repair cost / asset condition / damage)*
Operational outcome	Measures the operational impact of the hazard occurring **(Subcategories:** *operational cost / delay / safety / environment / revenue)*
Feature of a resilient system	Measures or quantifies attributes of a resilient system. Likely to be process metrics. **(Subcategories:** *risk assessment / adaptation planning / governance / investment plans)*[6]

3.3 Desktop study conclusion

This desktop study presented an overview of climate hazards considered by transport organisations and sectoral bodies as high priority. As evident in section 3.2.1, the source material provided an in-depth account of climate hazard impacts at an asset and outcome level, and utilised risk assessments to prioritise hazards. The prioritisation of hazards varied by sector, with precipitation and flooding being the most significant for aviation, road and rail sectors and sea level rise for the maritime sector.

Incidences of hazard and outcome measurement were also identified within the source material, with organisations across all sectors presenting metrics for these purposes. However, due to each organisation's unique objectives, assets, locations, exposures, vulnerabilities, and impacts, the metrics were organisation, asset or site specific. This limits the utility of these metrics at the scale of a transport mode or the transport system. This finding confirmed a working assumption (Section 3.1) that had been identified early within the project and directed the project team to consider features of a resilient system as a means for understanding the reason behind trends in resilience performance.

The desktop study provided a baseline of valuable information that was tested with stakeholders in the WS1 cross-modal workshop. Due to the volume of potential metrics identified, a summary of these metrics was presented to workshop attendees for their feedback - these are presented in Table 5 below. The metrics presented here are not geographically specific. The need for regionally specific metrics will be considered at WS3.

[6] In the context of emerging findings at WS2 and WS3, metric sub-categories may be further optimised and amended.

Table 4: Information presented to workshop attendees

Session 1			
Road	**Aviation**	**Maritime**	**Rail**
Priority hazards			
• Precipitation /Flooding • Storms (high wind) • High Temperatures • Drought	• Precipitation /Flooding • High Temperatures • Storms (high wind) • Drought	• Sea Level Rise • Storms (storm surge, windspeed and direction) • Precipitation / Flooding • High Temperatures	• Precipitation /Flooding • Drought • Storms (high wind) • High Temperatures
Cross-cutting hazard metrics			
• Met Office Weather Warning: Times per year/ Severity Level	• Met Office Heat/Cold Health Alerts: Times per year/ Severity Level	• EA/SEPA/NRW/RA Flood Warnings: Times per year/ Severity Level	
Specific Hazard Metrics			
• Number of hot days >35°C • Number of flooding hotspots on the network • Rainfall intensity (mm/h) • Wind gust speed (km/h) • Number of dry spells (10+ days with no rainfall)	• Number of days with >25mm rainfall • Number of days >25°C. • Number of dry spells (10+ days with no rainfall) • Wind gust speed (km/h)	• Windspeed exceeding 37 knots (overtopping risk) • Seasonal rainfall anomaly (%) • Storm surge thresholds (m)	• Number of hot days (annual) • Number of hot spells (3+ days) • Number of dry spells (10+ days with no rainfall) • Wind gust speed (km/h)
Asset level outcome metrics			
• (Road) Pavement condition (% in good condition) • (All) Asset deterioration • (All) Building structural damage >26°C • (All) Depreciation charges (attributed to climate) • (All) Estimated costs of inaction: physical asset damages (£)[7] • (All) Asset repair & replacement cost (CAPEX) • (All) Asset management costs (OPEX)	• (All) Asset deterioration • (Aviation) Max take-off weight affected >30°C • (All) Building structural damage >26°C • (All) Depreciation charges (attributed to climate) • (All) Estimated costs of inaction: physical asset damages (£) • (All) Asset repair & replacement cost (CAPEX) • (All) Asset management costs (OPEX)	• (All) Asset deterioration • (Aviation) Max take-off weight affected >30°C • (All) Building structural damage >26°C • (All) Depreciation charges (attributed to climate) • (Maritime) Number of safety incidents due to tidal conditions / dense fog / grounding in low water (e.g. grounding, navigational challenges). • (All) Estimated costs of inaction: physical asset damages (£) • (Maritime) Flood damage of harbour authority assets (£)	• (All) Asset deterioration • (All) Building structural damage >26°C • (All) Depreciation charges (attributed to climate) • (Rail) Rail faults: above 26°C, faults increase in likelihood x2.4 for each 1°C. • (Rail) Track geometry faults per 100km (weather attributed) • (Rail) Number of failures and incidents related to overhead line equipment • (All) Estimated costs of inaction: physical asset damages (£)

[7] Quantifies the estimated asset damage costs if no adaptive action is taken.

		• (All) Asset repair & replacement cost (CAPEX) • (All) Asset management costs (OPEX)	• (All) Asset repair & replacement cost (CAPEX) • (All) Asset management costs (OPEX)
Session 2			
Operational outcome categories			
• Delays	• Reputation	• Resultant costs	• Loss of revenue
• Safety	• Environment		
Operational outcome metrics			
• Delays: Delays to Passengers // Goods and cargo // No. people affected	• Cost: Operational costs e.g. delay-repay schemes // insurance costs // Regulatory compliance	• Safety: Reportable incidents (staff / public)	• Environment: Reportable compliance failures
Interdependencies			
• Power outages	• Availability of the SRN	• Capacity of third-party drainage systems	• Standard of protection provided by third party flood defences
• Telecommunications / ICT outage			

4 Cross-Modal Workshop

4.1 Overview

4.1.1 Workshop objective

By engaging with stakeholders through a cross-modal workshop, WS1 aimed to verify the priority climate hazards identified for each mode, identify potential metrics for monitoring hazards and outcomes and identify high level interdependencies between hazards and sectors. In combination with Workstream 2, the workshop findings will support the Workstream 3 activities to identify the gaps and outline steps for addressing them. The workshop also facilitated the introduction of the project to organisations who will be further engaged through 1-2-1 interviews at WS2.

4.1.2 Participants

Representatives from 26 transport and regulatory organisations attended the workshop for WS1. The full list of attending organisations is captured below:

- Association of Directors of Environment, Economy, Planning & Transport (ADEPT)
- British Aviation Group
- British Ports Association
- Civil Aviation Authority
- Climate Change Committee
- Defra
- Decarbonised, Adaptable and Resilient Transport Infrastructures (DARe Hub)
- East West Rail
- High Speed 1
- High Speed 2
- Hutchison Ports
- Manchester Airports Group
- Met Office
- National Infrastructure Commission
- National Highways
- National Air Traffic Services (NATS)
- Network Rail
- Office of Rail and Road
- Port of London
- Rail Safety and Standards Board (RSSB)
- Susteer
- Transport for Greater Manchester
- Transport for London
- Transport for West Midlands
- UK Roads Leadership Group (UKRLG)
- West Midlands Combined Authority
- Department for Transport

4.1.3 Discussion sessions

Engagement was conducted through two discussion sessions to structure the collection of feedback and facilitate both modal and cross-modal discourse.

Discussion session 1 grouped attendees by their transport mode and presented the priority hazards identified through the WS1 desktop study for their mode. Feedback was collected on the priority hazards and attendees provided suggestions on which additional hazards were important to their mode. Facilitators then directed discussions towards the measurement of priority hazards, presenting potential metrics identified from the desktop study and collecting suggestions on further metrics. Discussion session 1 closed by considering the impacts of climate hazards at an asset level. Feedback on the impacts and metrics used in measurement was collected.

Discussion session 2 was facilitated within cross modal groups to focus on operational outcomes, their measures and interdependencies. Attendees were first presented with potential operational metrics identified through the desktop study and their feedback on their suitability was captured. Discussion session 2 closed with a conversation on interdependence between transport modes and with other sectors, with facilitators recording organisations' thoughts on how these should be measured, and what data would ideally be shared.

The workshop ended with a brief conversation on the attributes of a resilient system – measures and capabilities that organisations can invest in to become more resilient to climate change and weather events.

4.2 Information Presented

Due to the volume of information extracted from the source material, and finite time available during the workshop, a representative sample of the desktop study findings was presented to attendees. The information presented is captured in Table 4 (page 13).

4.3 Feedback from attendees during the workshop

4.3.1 Priority hazards

4.3.1.1 Key points

Discussion sessions opened with attendees providing feedback on the priority hazards identified for their respective modes. While stakeholders were generally in agreement with the priority hazards identified for their sector, the utility of these lists was questioned. Feedback identified that the national scope of literature reviewed may mask priority hazards at a local level. Geographical, meteorological and other situational variance affect hazard impacts at a local scale, and this variability is lost when "priority" hazards are only identified at the national level. Individual groups agreed that hazard prioritisation can be useful, but only with an associated purpose, such as part of a decision-making process specific to a location or asset. Stakeholders identified the omission of sea level rise from priority hazards for road, rail and aviation sectors as the potential product of this national scale limitation.

Feedback also suggested that the division of hazards into discrete categories neglects combinations of hazards which can have a significant impact on assets and operations.

4.3.2 Hazard metrics

4.3.2.1 Key points

Feedback gathered during discussion session 1 on the use of climate hazard metrics showed organisations consider their utility at a sectoral level to be limited. Attendees agreed that the benefit of measuring climate hazard magnitude, incidence or threshold exceedance alone is limited, since these measures do not provide information on impacts (which is more valuable for stakeholders). For improving resilience to climate hazards, attendees thought it important to understand not just the weather warning, but also its consequence. Integrated metrics measuring weather attributed impacts (e.g. number of rail faults due to high temperature), were suggested to conceptually provide a clearer understanding of cause and effect.

Attendees also questioned the usefulness of hazard metrics as there are there are no sectoral-level thresholds (e.g. specific temperatures or rainfall intensities) that can be applied to climate variables. Attendees noted the difficulty of aggregating local thresholds into meaningful, nationally applicable metrics and suggested that thresholds are best applied at smaller scales.

Given the variance in requirement across spatial scales, asset groups and sectors, attendees suggested that where used, organisations should develop bespoke hazard incidence and threshold metrics, tailored to their requirements. Attendees also highlighted that national or broad hazard metrics would lose local scale high risks. Resource constraints were also noted by some organisations as significant inhibitors of sufficient data collection.

Stakeholders did however identify a potential application of hazard metrics in resilience planning. Suggestions were made that existing thresholds might be compared with projections of weather conditions to provide insight into asset and organisational resilience. Where projections exceeded current thresholds, an asset or organisational system could be considered unprepared. Metrics providing context on the impact of hazards such as ‘warnings not to travel’ were also considered as useful universal hazard metrics.

4.3.2.2 Mode specific feedback

Specific feedback captured in modal breakout groups gave insight into organisational priorities, summaries of which are captured below:

Road: Stakeholders from road organisations emphasised that the utility of hazard metrics varied significantly across distinct locations and asset groups. Measures of groundwater level and surface temperature were considered as potentially useful system-wide hazard metrics, yet tolerances and thresholds vary at a more granular level. It was also recognised that duration of events can be a significant metric to track as well as severity.

Rail: Stakeholders from rail organisations suggested that the proposed hazard metrics overlooked measurement of hazards that were significant on smaller spatial scales or in specific parts of the network (e.g. sea level rise). It was discussed that hazards which are significant only on smaller spatial scales could still have disproportionately large system-wide impacts as single localised failures have the potential to cause cascading impacts throughout the system, particularly if failures occur on key routes or interfaces. Stakeholders suggested a consideration of network value criticality when naming priority metrics, where priority hazards and their metrics would give weighted consideration to more crucial parts of the rail network. Discussion also addressed challenges of scale in weather forecasts, citing disparities between the forecasted weather and actualised local conditions. These disparities were considered as challenges for accurate hazard measurement.

Aviation and Maritime: Stakeholders from aviation and maritime sectors agreed on the infeasibility of producing representative sets of thresholds for their respective sectors. Both groups expressed an interest in measuring the climate-related damages and costs avoided (as a proxy for resilience achieved) and suggested that hazard thresholds had greatest utility when developed and managed by individual organisations.

4.3.3 Asset level outcome metrics

4.3.3.1 Key points

During the second section of discussion session 1, attendees gave their views on the optimal use and nature of asset level outcome metrics. Organisations discussed the value of insight from asset level outcome metrics, particularly when they can be aggregated at a systems level.

A potential primary use of these metrics by individual organisations was their facilitation of the tracking of damage and wider cost impacts from climate change. The insights organisations can draw through their tracking of asset level outcomes were said to be beneficial for building evidence bases to support business cases for investment and adaptation funding.

Limitations in the extent of insights that can be drawn from these metrics were also identified, especially related to the contextual nature of asset level outcome metrics, and their inability to measure interdependencies. Like the challenges faced with hazard metrics, asset-level outcome metrics were said to be highly specific to asset locations, groups and sectors making the determination of 'optimal metrics on a large-scale challenging. Attendees raised challenges associated with developing cross-sectoral metrics such as asset repair costs, due to differences in budget values and allocations. The internal use of asset repair cost as a metric of hazard impact was also discussed as imperfect, since where budgets are limited, spend on asset repair may fall short of its optimal amount.

Interdependencies were also discussed by stakeholders as challenging to quantify through asset-level metrics. Given the scope of asset-level metrics, they may provide context to outcomes, but they do not capture interdependence which was judged by the participants to be significant. Therefore, at a transport mode and transport system level, more focus should be given to operational outcome level metrics.

4.3.3.2 Mode specific feedback

Mode-specific feedback on asset-level outcome metrics was captured in breakout sessions, summaries of which are captured below:

Road: Stakeholders from the road sector suggested asset-level metrics are best considered by asset group or class and showed an interest in the use of asset-level metrics for the gauging of asset deterioration rates for their organisations. However, stakeholders questioned whether they would be of interest or provide value at transport mode or system level when at a high level of resolution. Road stakeholders also suggested measures of asset availability or journey availability to be potentially useful asset-level measures for climate hazard measurement (e.g. availability of the strategic road network, a metric identified by other users as useful for measuring interdependency risk). A challenge was raised about the desktop study's suggestion of pavement condition as a useful metric, since attendees did not consider that it captures sufficient information on the impacts of weather (e.g. deterioration due to hot weather or wet conditions). Stakeholders also noted the limited utility of asset-level metrics in measuring and understanding interdependencies, and emphasised the importance of this for the road network due to the scale of socioeconomic activity it supports.

Rail: Stakeholders from rail organisations noted the challenges of aggregating thresholds significant at a local level into meaningful national metrics, especially in the context of changing asset design and the resulting change in resilience. Consequently, stakeholders saw value in the development of regional metrics and indicators which they saw as providing greater value to operators.

Aviation and Maritime: Attendees noted the criticality of asset-level outcome metrics in qualifying business cases for investment. Representatives from both sectors therefore expressed the importance of quantitatively understanding impacts at an asset level. Specific measures of the cost of repairs and the reductions in asset lifespans due to climate hazards were identified as useful asset-level measures and were seen providing useful proxies for wider system resilience. Quantitative measures of loss avoidance such as the costs of maintenance, adaptation or clean-up were also discussed as asset-level measures with utility for attraction of investment. Representatives from both sectors agreed that wider impacts on their supply chains were crucial to capture and considered the use of hazard metrics useful in this cause.

4.3.4 Operational metrics

4.3.4.1 Key points

Session 2 collected feedback from attendees on the measurement of climate impacts at an operational level. The information presented categorised operational metrics into measures of operational cost, delay, safety, environmental regulatory compliance[8], and revenue.

Measures of system safety were considered by most as of significant importance both due to their direct implication of staff and user wellbeing, but also due to their cascading impacts on other operational outcomes. Discussions cited safety incidents and precautionary actions as a significant cause of cancellations and delays, rendering their measurement and control critical to organisational operations.

Representatives also discussed the utility of delay metrics in gauging operational outcomes. Alongside temporal measures of delays, seen as especially important for intra-sectoral comparison, attendees wanted to quantify wider performance outcomes from delays. Examples of metrics given by stakeholders included the on-time performance of transport and the value of cargo lost due to lateness. These measures facilitate cross-contextual comparisons to a greater degree than raw measures of time due to variance in average delay durations and impacts across sectors. However, participants differentiated between temporal measures of delay and cancellation outcomes. While sectors considered the nature of cancellations in different ways, their separation from mid-journey delay was considered important due to the differences in passenger experience. Furthermore, participants identified the value in measuring recovery in terms of return to service levels as it also captures a useful aspect of resilience.

Operational metrics for recording the impact of climate change on environmental impact and regulatory compliance were of lower priority for attendees than safety and delays. Reportable compliance metrics were suggested by the desktop study findings as a potential metric for environmental outcomes. Discussions showed interest in these metrics, yet no specific metrics were suggested. Interpretative challenges associated with environmental metrics were highlighted by organisations where compliance was considered to be an elusive and potentially moving target. Attendees noted that their level of compliance with environmental policy was interpreted by regulators through the context of underlying conditions and the perceived sufficiency of their preparedness. Stakeholders from the aviation sector did stress the importance of measuring the environmental impacts of their operations for communities, specifically through collecting information on air quality and noise, and associated the importance of this practice with legislated requirements which may be more challenging to meet as a result of climate change.

Operational costs and revenue losses were hypothesised by the desktop study to be largely resultant of other operational outcomes and therefore seen as metrics which could be used across modes. Attendees also considered operational costs and revenue losses as critical for making the business case for investment in adaptation measures. Discussions identified additional sources of cross-modal metrics such as corporate insurance and finance to be useful high-level measures of hazard impacts on organisational operations. Measures of incident cost such as lost customer revenue were also considered useful by attendees for more granular level insight. Therefore, there are many types of operational costs that could be affected by climate change and hazards so clear definitions of what costs to include in a cost metric would be necessary. Stakeholders emphasised however that costs and revenue losses alone do not describe operational impacts, especially due to the wider socioeconomic outcomes that fall out of their scope. Organisations were eager to consider the wider

[8] Examples include: water quality, air quality, biodiversity, noise, soil.

effect of their sector's performance on economic and social systems, yet recognised the challenges associated with measuring these impacts.

For the use of all operational metrics, organisations identified the need for a baseline to be established and expectations to be defined. This theme was relevant to all categories of outcome measure, and was chiefly interested in understanding customer, regulator and internal expectations of service provision or level. Organisations discussed the nature of reasonableness of service levels being set by regulators and policy makers due to its variance between different organisations and locations and stressed the importance of their awareness of expectations in their target setting and achievement. So, while expected service levels or provisions was identified as being key, how this is determined in practice must be managed with the input of all relevant stakeholders.

4.3.4.2 Measuring interdependencies and data sharing

Since the impacts of climate hazards extend beyond individual sectors and assets, organisations emphasised the importance of measuring interdependencies outside the transport sector. There are dependencies between transport modes as well as with water, power and telecommunications sectors and reciprocal interdependence of those sectors (and other sectors) on the transport sector. Stakeholders discussed their dependence on the water sector for drainage provision and water supply, and potential for significant cascading effects on their network due to flooding. Likewise, the sector's complete reliance on power and telecommunications networks was observed, and attendees expressed a strong interest in obtaining greater awareness of these systems' operational performance and resilience.

Interdependencies between transport modes were also recognised and discussed as important metrics for organisational operation. Stakeholders were cognisant of the effects of disruption of other sectors on their own and were eager to understand these impacts. Few specific measures of interdependence were discussed, yet representatives expressed an interest in understanding their interdependent stakeholders; the ways in which they exert influence; the ways in which they are influenced; and the nodes of their system that are most at risk from or impactful to other organisations.

Roads were unanimously identified by stakeholders as a key sector of influence. Availability of both the local and strategic road network influences the supply chain, staff and user movement of all other transport sectors significantly.

Stakeholders agreed that the management of interdependence is a key facet of their organisational resilience to climate change. Awareness of operational performance across other sectors was deemed critical in managing and understanding the resilience and performance of individual transport networks. Discussion raised the challenge of cross-sectoral differences in terminology and information collection for interdependence recognition. This awareness may be bolstered through collaborative approaches to data collection and analysis across organisations and sectors.

4.3.4.3 Other suggested measures

In addition to the categories of operational metrics identified by the desktop study, attendees suggested further operational outcomes for measurement.

Organisations expressed their need to measure social outcomes from climate hazards, especially the wider effect of disruption on accessibility of transport for users. The impact of restricted access to key institutions such as schools and hospitals was discussed as an important impact metric. The disproportionate impact of climate hazard disruptions on people with disabilities was also considered an important accessibility consideration, and stakeholders expressed interest in its measurement for abatement.

Construction and recovery time were also suggested by organisations as potentially insightful measures of climate hazard impact at an organisational level. Given the transport sector has significant construction projects underway, it is important for associated organisations to understand weather impacts on construction activities. Recovery/repair time was also highlighted as not being adequately measured currently but that it is important feature to measure as part of a systems resilience.

4.3.5 Features of a resilient system

Discussions among attendees on the features of a resilient system were limited due to time constraints. However, organisational aims did emerge through preceding discussions which represent stakeholder views on what a resilient transport system looks like. Organisations recognised the importance of measuring their own capabilities and identified the accurate measurement of hazard impacts, including through delays, damage and economic losses as well as the effectiveness of adaptation measures as key characteristics of a resilient system. Organisations highlighted that they would want to be able to assess the impact of the features/resilience capabilities on the actual desired outcome (improved response to weather events/climate change) but recognise that this is challenging. Furthermore, while the utility of metrics at a hazard and asset level were considered to be useful for an individual organisation, inter-organisational and cross-sectoral metrics were deemed to improve resilience of transport system at a whole system or holistic level. Finally, a collaborative approach to data collection was suggested as a key feature of a resilient transport sector as a whole.

5 Synthesis of findings

5.1 Key points taken from literature and confirmed by stakeholders

Desktop study findings summarised in Section 3.3 provided an insight into current organisational practices of hazard and hazard impact measurement across asset and organisational levels. Section 5.1 analyses these findings alongside feedback gathered through stakeholder engagement (Section 4.3).

The desktop study concluded by observing the granularity of metrics at a sectoral, organisational, asset type or site-specific level, and noted the limited utility of these measures for data sharing and understanding of cross-sectoral interdependencies. Stakeholder engagement affirmed these findings in some ways, where attendees recognised the lack of sector or industry-wide metrics for the measurement of climate hazards and their impacts and recognised their utility for policy development and resilience planning.

However, stakeholders were also keen to emphasise that certain measures were not easily aggregable to sector or industry scales and were best developed and measured by organisations individually. While hazard metrics were recognised as being useful to understand trends in exposure, they do not capture vulnerability and so are less valuable unless also combined with other data points, for example to attribute an event or impact to a weather or climate cause. For asset-level impact measurements, attendees emphasised their necessity for assessing damage and cost internally as well as for their use in business cases, yet attendees questioned their utility for characterising sectors or assessing interdependence due to their inherent local scope, and considerable variations across spatial scales and asset types.

Metrics measuring operational outcomes were identified by both the desktop study and stakeholder engagement discussions to offer the greatest potential for industry wide and cross sectoral analysis. Discussions highlighted the importance of setting baseline operational levels or expectations to identify variations from these. These metrics were also considered to offer the greatest utility for developing business cases for investing in climate resilience due to their expository measures of climate damage. Organisations were particularly interested in developing combination metrics, where attributions to climate hazards could be made, allowing for easy quantification of damage and delay, and the strengthening of evidence bases for garnering investment.

In sum, organisations saw the greatest utility in metrics measuring operational outcomes, due to their utility in building business cases, and for their potential to provide information to facilitate cross organisational or sectoral information sharing. Organisations also considered the utility of asset-level outcome metrics for internal use yet were unsure on their applicability or feasibility of development at a higher level. Hazard metrics measured alone were deemed to be of least use, since they offered no detail on the implications for assets or operations, but they are useful to inform combination or weather attribution metrics. For both hazard and asset-level outcome measurement, their use is most effective at local scales.

5.2 Key points to be taken forwards to WS2 and WS3

The workshop provided in-depth feedback on the desktop study findings that were presented. From the discussions and that feedback, a number of significant themes that are fundamental to the topic of measuring climate resilience also emerged. These are discussed further below.

- **Different aspects of climate resilience** – Both the desktop study and the workshop identified that there are multiple aspects of climate resilience all of which are important to the transport sector.

For example: readiness, responsiveness, recovery & renewal[9]. Articulating these aspects will help to determine which of them need greater focus for improvement and the metrics which will help to measure that improvement. Groupings will be explored as part of WS3.

- **Transport organisation resilience is different to transport system resilience** – Individual transport organisations have clearly defined remits and specific objectives. How they approach resilience and the metrics they each use to measure it is driven largely by those factors. As the transport system as a whole has broader objectives and a much more significant scope, the metrics used to measure resilience will need to be adjusted or different altogether. This will be explored further within WS3.
- **Metrics need a purpose** – There are many metrics that can be defined in relation to one aspect of resilience. However, they ultimately need a purpose to provide value in some way. As each transport organisation each has a unique remit and objectives, the resilience related metrics they measure have a specific organisational purpose. For example: the temperature threshold to impose speed restrictions on a specific section of more vulnerable track; or total annual number of passengers affected by weather attributed events disaggregated by asset type and failure mode (to identify key vulnerabilities and therefore priority assets for investment). In their current form these metrics provide value to the transport organisations but they only provide insight on the transport system resilience if equivalent underlying data is being collected across the whole transport system such that it can be aggregated and disaggregated as required at a transport mode or system level. Therefore, the metrics defined at a transport mode or system level must be defined to support a specific purpose and they must be designed such that the same data can be collected across the transport mode or system. The purpose of each metric will be considered further within WS3.
- **Metric complexity: Weather attribution** – Due to differences in resilience maturity across the transport sector transport organisations face challenges to attribute asset impact or outcome impacts to weather or climate related events. Furthermore, there are often multiple contributing factors influencing an outcome such as asset deterioration. Data collection challenges within organisations limit their abilities to attribute or determine contribution of weather or climate to specific impacts or metrics. This will be explored further within WS2 stakeholder interviews.
- **Metric complexity: Definitions** – There are no agreed or common definitions within and across transport sectors in relation to resilience metrics. For example, even simple terms such as 'delays' and 'costs' are complex in practice because there is no common agreement of whose delays and which costs would be captured within a metric. Without common or agreed definitions, key data may be hidden, or insignificant data may be amplified. These potential gaps will be evaluated at WS3.
- **Resilience maturity across the transport sector** – It is recognised that there is a disparity in resilience maturity of transport organisations across the sector. However, there is no definition of resilience maturity or any metrics which allow this to be measured or understood. In order to target resilience improvements there needs to be a clear approach to determining resilience maturity that can be applied to transport sector organisations to identify the support they need to improve their maturity. Determining features of a resilient transport system will support this[10]. This will be considered further within WS3.
- **Significance of interdependencies** – The transport sector is a key system within the UK's socio-economic network. It both relies upon many other sectors and networks while also being relied upon by them. Therefore, the resilience of the transport network is heavily dependent on the resilience of these other sectors and networks. Going forwards, ensuring the resilience of the transport system will require an increasing understanding of interdependencies. This will be considered further within WS3.
- **Performance levels** – Determining the expected service level for normal situations and under hazard conditions supports the definition of thresholds for what are 'acceptable' operational

[9] This example is taken from British Standard 65000

[10] The Rail Safety and Standards Board's Sustainable Rail Blueprint Strategy provides a useful starting point.

impacts. Organisations expressed their interest in understanding their stakeholders' expectations on performance in normal and hazard conditions so that they are better able to plan for the future. This will be explored further in WS3.

6 Conclusion and Next Steps

WS1 presents its findings from a desktop study and stakeholder engagement to ascertain priority hazards for the transport sector, and the optimal use of metrics in their measurement. Desktop study findings are contextualised and critiqued through workshop feedback and form an evidence base for further work at WS2 and WS3.

Findings on the priority hazards for individual transport sectors suggested a relative success of the desktop study in identifying the hazards most critical to individual transport modes. While the priority hazards were generally agreed by stakeholders to represent the greatest existential threats to their sectors, the omission of local, high-impact events was identified as a limitation of the process due to the national scope of the literature. The effects of compound events on organisations were also said to be overlooked by the desktop study process.

Findings on the utility of metrics for the transport sector showed that measures of operational outcomes were favoured by organisations for their utility in forming business cases and understanding interdependencies. Metrics measuring hazards and asset-level impacts are of value to the organisations collecting them but their value when aggregated at a transport mode or sector level are potentially limited due to their granular organisational scope and high resolution. Generically measuring hazards was questioned, since stakeholders' infrastructure has unique vulnerabilities associated with hazard magnitudes, incidences and threshold exceedances but the value of capturing hazards as the cause of impacts was agreed. Asset-level impact metrics were considered useful especially when aggregated at an organisational level for internal use, and for informing wider operational awareness.

The findings of WS1 will guide the design of further stakeholder engagement at WS2 to uncover what metrics and data are currently in use by organisations and how these could be used to understand the impacts of climate change on the transport sector, and its resilience to those impacts. The findings of WS1 will then be compared with those of WS2 during analysis at WS3 to understand the gap between potential and current measurement of climate hazards and their impacts to inform high-level roadmaps that address the gaps.

7 Appendices

Appendix 1: Literature reviewed

Table 5 lists the 82 publications reviewed for the desktop study conducted at WS1, the relevant sector, their type and source.

Table 5: Source material

Document Name	Sector	Type	Source
Heathrow Airport ARP3	Air	ARP3	Open-Source Research
Birmingham Airport ARP3	Air	ARP3	Open-Source Research
Edinburgh Airport ARP3	Air	ARP3	Open-Source Research
Gatwick Airport ARP3	Air	ARP3	Open-Source Research
Glasgow Airport ARP3	Air	ARP3	Open-Source Research
Luton Airport ARP3	Air	ARP3	Open-Source Research
Manchester Airports Group ARP3	Air	ARP3	Open-Source Research
Climate Change Risks for European Aviation	Air	Industry Authority	Open-Source Research
Peel Ports Group Climate Change Adaptation Report	Maritime	ARP3	Open-Source Research
Port of Dover ARP3 Report	Maritime	ARP3	Open-Source Research
Port of London Authority ARP3 Report	Maritime	ARP3	Open-Source Research
ABP ARP3 Report	Maritime	ARP3	Open-Source Research
British Ports Association: Climate change and ports Impacts and adaptation strategies	Maritime	CCIA	Open-Source Research
HS2 Climate Adaptation ARP Report	Rail	ARP3	Open-Source Research
Network Rail Third Adaptation Report December 2021	Rail	ARP3	Open-Source Research
NETWORK RAIL APPENDIX A integrated ARP3 climate risk assessment	Rail	ARP3	Open-Source Research
TFL adaptation reporting power 3	Rail	ARP3	Open-Source Research
Identification of Climate Resilience Opportunities and metrics in Financing Operations (Inter-American Development Bank - IDB)	Transport	IDB Report	Open-Source Research
Transport system resilience: Summary and Conclusions (International Transport Forum - ITF)	Transport	ITF Report	Open-Source Research
US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	Transport	NCA5	Open-Source Research
National Highways ARP3 Report	Road	ARP3	Open-Source Research
Climate Change Adaptation and Transport Infrastructure NatCen	Road	Industry Authority	Open-Source Research
DfT Climate Risk Assessment Guidance for the Transport Sector	Transport	Industry Authority	Open-Source Research
Nestrans 2040: THE REGIONAL TRANSPORT STRATEGY FOR THE NORTH EAST OF SCOTLAND	Transport	Industry Authority	Open-Source Research
RSSB: Tomorrow's Railway and Climate Change Adaptation: Final Report, Task 3: Metrics evaluation appendices	Rail	Industry Authority	Provided by DfT
RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Rail	Industry Authority	Provided by DfT
CFRF: Oxford Adaptation Targets & Metrics	General	Best practice report	Open-Source Research
Federal Ministry for Economic Cooperation and Development: Repository of Adaptation Indicators	Transport	Industry Authority	Open-Source Research

A Framework and Principles for Climate Resilience Metrics in Financing Operations	General	Industry Authority	Open-Source Research
TACTRAN: Climate Change Adaptation Policy Statement	Transport	Industry Authority	Open-Source Research
Climate Ready Clyde: Adaptation Strategy and Action Plan	Transport	Industry Authority	Open-Source Research
UK CCRA3: Technical Report Chapter 4: Infrastructure	Transport	CCRA3	Open-Source Research
Queensland Government: Climate Change and Natural Hazards Risk Assessment Guideline	Road	Industry Authority	Open-Source Research
TfNSW (Transport for New South Wales) Climate Risk Assessment Guidelines	Rail	Industry Authority	Open-Source Research
Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	Transport	CCRA3	Open-Source Research
European Climate Risk Assessment	Transport	CRA	Open-Source Research
Forth Ports (Tilbury) Tilbury Flood Risk Summary	Maritime	ARP4	Provided by DfT
Gatwick Airport ARP4	Air	ARP4	Provided by DfT
Office of Rail and Road ARP4	Rail / Road	ARP4	Provided by DfT
Highlands and Islands Airports Limited ARP4	Air	ARP4	Provided by DfT
Climate Change Committee: CCRA4 Template I7	Air / Maritime	CCRA4	Provided by DfT (from CCC)
Climate Change Committee: CCRA4 Template I5	Road	CCRA4	Provided by DfT (from CCC)
Climate Change Committee: CCRA4 Template I6	Rail	CCRA4	Provided by DfT (from CCC)
National Highways ARP4: Climate Change and the strategic Road Network	Road	ARP4	Provided by DfT
National Highways Appendix A ARP4	Road	ARP4	Provided by DfT
Birmingham Airport ARP4	Air	ARP4	Provided by DfT
Civil Aviation Authority ARP4	Air	ARP4	Provided by DfT
Edinburgh Airport ARP4	Air	ARP4	Provided by DfT
London Luton Airport CCAR	Air	CCAR	Provided by DfT
NATS ARP4: Climate risk and adaptation progress report	Air	ARP4	Provided by DfT
NATS ARP4 Risk assessment & action plan	Air	ARP4	Provided by DfT
Newcastle Airport ARP4	Maritime	ARP4	Provided by DfT
Groveport ARP4	Maritime	ARP4	Provided by DfT
Teesport & Hartlepool ARP4	Maritime	ARP4	Provided by DfT
Peel Ports Group ARP4	Maritime	ARP4	Provided by DfT
Port of Dover ARP4	Maritime	ARP4	Provided by DfT
Port of London Authority ARP4	Maritime	ARP4	Provided by DfT
Arriva Rail London Climate Risk Assessment ARP4	Rail	ARP4	Provided by DfT
HS2 ARP4	Rail	ARP4	Provided by DfT
Network Rail ARP4	Rail	ARP4	Provided by DfT
South Eastern Railway ARP4	Rail	ARP4	Provided by DfT
TFL ARP4 (full report)	Rail	ARP4	Provided by DfT
TFL ARP4 (non-technical summary)	Rail	ARP4	Provided by DfT
National Highways Performance Monitoring Statements Year end 2023-24	Road	Performance Monitoring Statements	Open-Source Research
Birmingham Airport: Climate Change Adaptation Progress Report	Air	Adaptation progress report	Open-Source Research

Port of London Authority: Annual Report 2023	Maritime	Annual Report	Open-Source Research
Heathrow Airport Annual Report 2023	Air	Annual Report	Open-Source Research
Birmingham Airport Annual Report 2022-2023	Air	Annual Report	Open-Source Research
Gatwick Airport: Monthly Performance Report, November 2024	Air	Monthly Report	Open-Source Research
London Luton Airport Financial Statements 2020	Air	Financial Statement	Open-Source Research
Manchester Airports: Annual Report & Accounts 2024	Air	Annual Report	Open-Source Research
Peel Ports Annual Report 2023	Maritime	Annual Report	Open-Source Research
Peel Ports ESG & Sustainability Annual Report 2024	Maritime	Annual Report	Open-Source Research
Port of Dover: Annual Report & Accounts 2023	Maritime	Annual Report	Open-Source Research
Associated British Ports: Annual Report and Accounts 2023	Maritime	Annual Report	Open-Source Research
Edinburgh Airport: Climate Change Adaptation Report 2024	Air	CCAR	Open-Source Research
Eurocontrol Network Operations Report 2022	Air	Annual Report	Open-Source Research
Forth Ports PMSC ANNUAL REVIEW 2023	Maritime	Annual Report	Open-Source Research
Highlands and Islands Airports Limited ARP4	Air	Annual Report	Open-Source Research
Inter-American Development Bank: Framework and principles for Climate Resilience Metrics	General	Best practice report	Open-Source Research
BSI Standards Publication	General	Best practice report	Open-Source Research
Climate Sense: Benchmarking & capacity development	General	Best practice report	Open-Source Research

Appendix 2: Impact Chain Extracts

Table 6 presents the entire list of complete impact chains created during the desktop study process. Green cells represent logical inferences that were made from hazard descriptions.

Table 6: Impact chain extracts

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Overheating of assets	Overheating of airfield structures	Expansion of concrete/ asphalt	Increased rate of material degradation	Delays in service		
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Overheating of assets	Overheating of equipment	Overheating of sensitive equipment	Less reliance /lesser performance of sensitive equipment	Delays in service		
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Decreased air density	Less lift created by planes	Decreases in MTOW	Delays in service			
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Overheating of assets	Overheating of indoor environments	Increased reliance on cooling equipment	Increased reliance on energy suppliers	Delays in service		
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Nearby residents leaving windows open at night	Greater disturbance on local communities	Complaints /Changes in Regulation	Delays in service			
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Exceedance of max. working temperature	Less comfortable environments for staff / passengers	Delays in service				
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Decreased air density	Less lift created by planes	Increased ground speed when landing	Harder and faster landings	Delays in service		
High Temperature	Edinburgh Airport ARP3	High Temperatures	Change to local animal habitats	Greater spread of pests/disease	Reduced public confidence in air travel	Delays in service			

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Precipitation / Flooding	Edinburgh Airport ARP3	Excessive Rainfall	Rise in groundwater level	Subsidence/ water ingress into buildings	Delays in service				SEPA flood warning data and river levels.
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Change to local animal habitats	Change to environmental consideration /monitoring	Delays in service				
Low Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Temperatures	Accumulation of ice / snow on surfaces	Increased danger of traveling	Delays in service				
Low Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Temperatures	Increased reliance on heating equipment	Increased reliance on energy suppliers	Increased impact of energy deficiencies	Delays in service			
Low Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Temperatures	Less comfortable environments for staff /passengers	Damage to health and wellbeing of staff / passengers	Delays in service				
Drought	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Rainfall	Decreased river flow	Debris caught in drainage	Accumulation of debris in drainage network	Blockage of drainage network	Damage	Delays in service	
Drought	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Rainfall	Declining water table	Water usage limits	Delays in service				
Drought	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Rainfall	Declining water table	Decreased surface water levels	Degradation in soil quality	Drought stress on plants and landscaped area.	Damage	Delays in service	
Storms	Climate Change Risks for European Aviation	High Windspeed	Decrease in vertical and horizontal flight efficiency	Delays in service					
High Temperature	Climate Change Adaptation and Transport Infrastructure NatCen	High Temperatures	Decreased air density	Less Lift Created by Planes	Decreases in MTOW	Delays in service			

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Reduced visibility	Danger for vehicles and aircraft	Delays in service				
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Less comfortable working environment for outside workers	Decrease in productivity of staff	Delays in service				
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Exceedance of drainage capacity	Pluvial flooding	Release of pollutants	Delays in service			
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Disrupting of supply chains	Strain on resources	Delays in service				
Storms	Climate Change Adaptation and Transport Infrastructure NatCen	Powerful Storm Event	High windspeed	Damage to electrical equipment	Delays in service				
Precipitation / Flooding	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	Intense rainfall	Decreased vegetation cover	Increased surface runoff	Pluvial flooding	Delays in service			
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Fluvial flooding	Inundation of site	Delays in service				
Precipitation / Flooding	Glasgow Airport ARP3	Intense rainfall	Pluvial flooding	Inundation of site	Inundation of road network	Difficulty for staff and customers to travel around / to the site	Delays in service		
Precipitation / Flooding	Gatwick Airport ARP3	Intense rainfall	Saturation of electrical equipment	Failure of electrical equipment	Delays in service				No. Days with >25mm ppt
Precipitation / Flooding	Heathrow Airport ARP3	Intense rainfall	Exceedance of drainage capacity	Pluvial flooding	Delays in service				Threshold: Precipitation >25mm / hr.

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Precipitation / Flooding	Heathrow Airport ARP3	Intense rainfall	Pluvial flooding	Delays in service					Water level >13.7m AOD at Clock house Lane Pit Modelling: Stress testing airport drainage model
Global circulation	Climate Change Risks for European Aviation	Changes in Wind Patterns	Changes in navigational processes	Delays in service					
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Overheating of assets	Exposure of flammable materials to heat	Fire Risk	Delays in service			
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Decreased air density	Less lift created by planes	Lower efficiency of engines	More pollutants in air	Delays in service		
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Decreased air density	Less lift created by planes	Increased ground speed when landing	Harder and faster landings	Accumulation of rubber on runway	Delays in service	
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Overheating of assets	Overheating of airfield structures	Expansion of materials	Increased rate of material degradation	Delays in service		
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Decreased air density	Less Lift Created by Planes	Delays in service				
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Overheating of assets	Overheating of airfield structures	Thermal expansion of concrete/ asphalt	Increased rate of material degradation	Delays in service		
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	High Temperatures	Overheating of assets	Overheating of airfield structures	Expansion of concrete/ asphalt	Increased rate of material degradation	Delays in service		

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
High Temperature	Transport system resilience: Summary and Conclusions (International Transport Forum - ITF)	High Temperatures	Decreased air density	Less Lift Created by Planes	Existing infrastructure obsolete	Changes to schedule/ operations	Delays in service		
High Temperature	Luton Airport ARP3	High Temperatures	Exceedance of max. working temperature	Less comfortable environments for staff / passengers	Decrease in worker productivity/ number of working days	Greater time required to perform works	Delays in service		Max. take-off weight affected at >30°C / Work ceases at >28°C.
High Temperature	Luton Airport ARP3	High Temperatures	Decreased air density	Less Lift Created by Planes	Decreases in MTOW	Delays in service			Max. take-off weight affected at >30°C
High Temperature	Luton Airport ARP3	High Temperatures	Overheating of assets	Overheating of indoor environments	Increased reliance on cooling equipment	Inadequate performance of cooling equipment	Less comfortable environments for staff / passengers	Delays in service	Work ceases at >28°C High temperature plan from >26°C
High Temperature	Luton Airport ARP3	High Temperatures	Overheating of assets	Exposure of flammable materials to heat	Fire damage	Delays in service			
High Temperature	Luton Airport ARP3	High Temperatures	Overheating of assets	Overheating of airfield structures	Expansion of concrete/ asphalt	Increased rate of material degradation	Delays in service		Increased risk of building structural damage at > 26°C
Precipitation / Flooding	Glasgow Airport ARP3	Intense rainfall	Increased surface runoff	Pluvial flooding	Delays in service				
High Temperature	Birmingham Airport ARP3	High Temperatures	Exceedance of aviation fuel temperature flashpoint	Ignition of fuel	Fire	Delays in service			Number of hot days (days with temp >25°C)
High Temperature	Birmingham Airport ARP3	High Temperatures	Overheating of assets	Overheating of indoor environments	Increased reliance on cooling equipment	Delays in service			Temperature > 28°C - 30°C
High Temperature	Gatwick Airport ARP3	High Temperatures	Overheating of assets	Overheating of indoor environments	Inadequate performance of cooling equipment	Less comfortable environments for staff / passengers	Delays in service		
High Temperature	Gatwick Airport ARP3	High Temperatures	Overheating of assets	Overheating of indoor environments	Overheating of sensitive equipment	Inadequate performance of sensitive equipment	Delays in service		

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
High Temperature	Birmingham Airport ARP3	High Temperatures	Overheating of assets	Overheating of airfield structures	Expansion of concrete/ asphalt	Increased wear on assets	Increased repair and maintenance requirements	Delays in service	Number of hot days (days with temp >25°C)
Precipitation / Flooding	Edinburgh Airport ARP3	Intense rainfall	Fluvial flooding	Inundation of site	Delays in service				SEPA flood warning data and river levels.
Precipitation / Flooding	Edinburgh Airport ARP3	Intense rainfall	Exceedance of drainage capacity	Pluvial flooding	Inundation of site	Inundation of sub-structures	Damage to electrical assets	Delays in service	
Drought	Manchester Airports Group ARP3	Low Rainfall	Declining water table	Water usage limits	Delays in service				
High Temperature	Heathrow Airport ARP3	High Temperatures	Exceedance of max. working temperature	Cessation of operational / maintenance activities	Greater time required to perform works	Delays in service			Outside temperature > 30°C
High Temperature	Heathrow Airport ARP3	High Temperatures	Overheating of assets	Overheating of indoor environments	Inadequate performance of cooling equipment	Less comfortable environments for staff / passengers	Delays in service		Building temperature > 24°C (winter) OR 25°C (summer)
High Temperature	Heathrow Airport ARP3	High Temperatures	Exceedance of aviation fuel temperature flashpoint	Ignition of fuel	Fire	Fire damage	Damage	Delays in service	
High Temperature	Heathrow Airport ARP3	High Temperatures	Overheating of assets	Overheating of airfield structures	Increased wear on assets	Damage to structural integrity of airfield structures	Damage	Delays in service	Temperature > 32°C
Drought	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	Low Rainfall	Declining water table	Decreased surface water levels	Degradation in soil quality	Water usage limits	Dust Storms	Delays in service	
Sea level rise	European Climate Risk Assessment	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Delays in service				
Sea level rise	US Climate Resilience Toolkit NCA5 Ch13 transportation	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Delays in service				

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Sea level rise	Climate Change Risks for European Aviation	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Closure of site	Relocation of assets	Delays in service		
Precipitation / Flooding	Glasgow Airport ARP3	Intense rainfall	Pluvial flooding	Inundation of site	Inundation of road network	Difficulty for staff and customers to travel around / to the site	Delays in service		
Storms	Manchester Airports Group ARP3	High Windspeed	Increased stress on infrastructure	Danger to assets and people	Delays in service				
Storms	Manchester Airports Group ARP3	Intense rainfall	Exceedance of drainage capacity	Pluvial flooding	Water Ingress	Delays in service			
Storms	Glasgow Airport ARP3	High Windspeed	Dislodging of debris	Debris swept across site	Delays in service				
Storms	Birmingham Airport ARP3	High Windspeed	Dislodging of debris	Transport of debris	Debris swept across site	Interruptions of operations	Delays in service		Projection: Wind speed
Snowfall	Glasgow Airport ARP3	Snowfall	Visibility constraint	Reduced mobility	Delays in service				
Drought	Gatwick Airport ARP3	Low Rainfall	Decrease in water availability	Water usage limits	Delays in service				No. Dry spells (10+ days with no ppt)
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Damage to green infrastructure	Wildfires/ Dust Storms	Delays in service				
High Temperature	Gatwick Airport ARP4	High Temperatures	Damage to green infrastructure	Ignition of green infrastructure	Visual impairments	Delays in service			
Low temperature	Climate Ready Clyde: Adaptation Strategy and Action Plan	Low Temperatures	Increased frequency of freeze - thaw cycles	Destabilisation of embankments and slopes	Damage	Delays in service			Geotechnical stability assessments and repair intervals.
Precipitation / Flooding	Climate Ready Clyde: Adaptation Strategy and Action Plan	Coastal Erosion	Damage	Delays in service					Frequency of flood-induced damages and repair costs.
High Temperature	Climate Ready Clyde: Adaptation Strategy and Action Plan	High Temperatures	Overheating of assets	Overheating of equipment	Damage to ICT infrastructure	Delays in service			Frequency of service disruptions and

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
									thermal tolerance testing.
Precipitation / Flooding	CFRF: Oxford Adaptation Targets & Metrics	Intense rainfall	Pluvial flooding	Inundation of road network	Disruption to public and private transport	Disruption to supply chains	Damage	Delays in service	Losses of GDP in percentage per year due to extreme rainfall. Numerator = total amount of quantified losses and damages on infrastructure due to extreme rainfalls in one year; Denominator = GDP of the respective year; Result *100
Weather Extremes	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Changes to Climate	Earthworks failures	Damage	Delays in service				Earthwork failures: Measures the annual number of rock falls, soil slips, slides or flows in a cutting, natural slope or embankment on running lines. (Network Rail)
Weather Extremes	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Changes to Climate	Undue stress placed on assets	Increased rate of asset deterioration	Damage	Delays in service			Asset failures: Total number of incidents causing train delay where the cause is the responsibility of network rail. (Network Rail).
Precipitation / Flooding	Climate Ready Clyde: Adaptation Strategy and Action Plan	Intense rainfall	Pluvial flooding	Inundation of road network	Disruption to public and private transport	Delays in service			Frequency of transport delays due to slope or embankment failures.

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Storms	Climate Ready Clyde: Adaptation Strategy and Action Plan	Powerful Storm Event	Increased rate of vegetation spread over track	Increased vegetation management requirements	Delays in service				Frequency of vegetation management and related incident reports.
Storms	RSSB: Tomorrow's Railway and Climate Change Adaptation: Final Report, Task 3: Metrics evaluation appendices	High Windspeed	Dislodging of debris	Obstruction on track	Delays in service				Number of trees on the line: Reported by drivers, however don't necessarily capture the associated weather event.
Precipitation / Flooding	UK CCRA3: Technical Report Chapter 4: Infrastructure	Intense rainfall	Saturation of ground	Subsidence	Damage	Delays in service			PROJECTION: Outcomes based on outputs from 4c global warming scenario.
Precipitation / Flooding	CFRF: Oxford Adaptation Targets & Metrics	Intense rainfall	Increased surface runoff	Exceedance of drainage capacity	Pluvial flooding	Delays in service			No. of properties in climate-adjusted 1-in100-year flood zone: Based on a measurement of future climate-adjusted 1-in100-year flood zones, usually assumed to be without flood protection measures
Precipitation / Flooding	UK CCRA3: Technical Report Chapter 4: Infrastructure	Intense rainfall	Saturation of ground	Destabilisation of ground	Landslides	Damage	Delays in service		Costs incurred due to rainfall-induced landslides
Precipitation / Flooding	TACTRAN: Climate Change Adaptation Policy Statement	Intense rainfall	Pluvial flooding	Inundation of road network	Isolation of rural population	Delays in service			
Weather Extremes	CFRF: Oxford Adaptation Targets & Metrics	Changes to Climate	Undue stress placed on assets	Increased rate of asset deterioration	Damage	Delays in service			Costs of damages to businesses due to delays caused by flooding, storms and other

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
									extreme weather events per year (UK)
High Temperature	CFRF: Oxford Adaptation Targets & Metrics	High Temperatures	Overheating of assets	Overheating of equipment	Damage	Delays in service			Number of hot days with complimenting commentary of impacted infrastructure
Sea level rise	Climate Change Adaptation and Transport Infrastructure NatCen	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Reduced clearance under bridges	Damage	Delays in service		
Storms	Nestrans 2040: The Regional Transport Strategy	High Temperatures	Overheating of assets	Damage	Delays in service				
Precipitation / Flooding	Nestrans 2040: The Regional Transport Strategy	Intense rainfall	Pluvial Flooding	Damage	Delays in service				
Sea level rise	Nestrans 2040: The Regional Transport Strategy	Sea Level Rise	Overtopping of coastal defences	Inundation of coastal areas	Damage	Delays in service			Monitoring: Coastal erosion data is recorded / available for Aberdeen City and Aberdeenshire coastline.
Drought	Nestrans 2040: The Regional Transport Strategy	Low Rainfall	Low soil moisture	Decreased stability of slopes	Landslides	Delays in service			
Marine currents	Peel Ports Group Climate Change Adaptation Report	Changes to Marine Currents	Changed hydrographical conditions	Changes to patterns of sedimentation	Increased dredging / disposal requirements	Delays in service			Results of hydrographic surveys
Sea level rise	British Ports Association: Climate change and ports Impacts	Sea Level Rise	Increase in tidal range	Reduced access at low tide	Navigational / scheduling challenges	Delays in service			

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
	and adaptation strategies								
Drought	Port of London Authority ARP3 Report	Low Rainfall	Decreased river flow	Increased turbidity	Increased pollutant concentration in waterways	Ecological damage	Damage	Delays in service	
Sea level rise	ABP ARP3 Report	Sea Level Rise	Change in port depth	Changes to customer base	Asset systems requiring replacement	Delays in service			
Marine Currents	TACTRAN: Climate Change Adaptation Policy Statement	Coastal Erosion	Erosion of roads / transport routes	Damage	Delays in service				
Storms	Transport system resilience: Summary and Conclusions (International Transport Forum - ITF)	Powerful Storm Event	Increased wave height	Damage to ships	Loss of life / cargo	Damage	Delays in service		
Drought	Port of London Authority ARP3 Report	Low Rainfall	Decreased river flow	Increased turbidity	Changed sediment transport / Deposition	Decreased depth / berth	Navigational Challenges	Delays in service	
Drought	Port of Dover ARP3 Report	Low Rainfall	Decrease in water availability	Shortage of water supply	Water usage limits	Delays in service			DHB (Dover Harbour Board) monitor water usage for all vessels.
Drought	European Climate Risk Assessment	Low Rainfall	Decreased river flow	Reduced navigation capacity	Impact on inland waterway transport	Delays in service			
Sea level rise	Port of London Authority ARP3 Report	Low Rainfall	Decreased river flow	Decreased vessel movement capacity	Delays in service				Records no. weather-related near-misses / minor incidents: Due to tidal conditions / dense fog / grounding in low-water. Records pilotage service

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
									disruptions: Data collected on no. vessel delays and pilots being overcarried due to strong winds / poor weather conditions.
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation	High Temperatures	Exposure of flammable materials to heat	Ignition of flammable materials	Damage to electricity supply assets	Interruption to electricity supply	Delays in service		
High Temperature	Port of Dover ARP3 Report	High Temperatures	Exceedance of max. working temperature	Heat-related illnesses	Decrease in worker productivity/ number of working days	Delays in service			
Storms	European Climate Risk Assessment	Sea Level Rise	Increased wave agitation	Disruption of port operating hours	Delays in service				
Snowfall	Port of Dover ARP3 Report	Snowfall	Settling of snow on access points	Incapacitation of site road network	Reduced mobility	Delays in service			
High Temperature	Port of London Authority ARP3 Report	High Temperatures	Overheating of assets	Overheating of roads	Degradation of riverine structures	Failure of riverine structures	Damage	Delays in service	
High Temperature	ABP ARP3 Report	High Temperatures	Increase in leisure boating	Collisions with smaller craft	Delays in service				
Storms	Port of Dover ARP3 Report	High Windspeed	Increased stress on infrastructure	Damage to electricity grid infrastructure	Severed electricity supply	Electrical blackouts	Delays in service		Wind speeds (monitored): >37 knots: Overtopping of Admiralty pier >45 knots: Vessels cause damage to berths >55 knots: Port is closed Damage reports
Drought	British Ports Association: Climate change and ports Impacts	Low Rainfall	Decrease in water availability	Water usage limits	Inhibition of operations	Delays in service			

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
	and adaptation strategies								
Low Riverine Flow	Transport system resilience: Summary and Conclusions (International Transport Forum - ITF)	Low Rainfall	Decreased river flow	Inland navigational challenges	Delays in service				
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Powerful Storm Event	Increased wave height	Structural damage to bollards	Damage				
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Changes to Ocean Temperature	Habitat alteration	Species migration	Novel challenges with new ecosystem	Delays in service			
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Changes to Ocean Temperature	Increased algal growth	Increased biofouling of maritime assets	Increased requirements for maintenance	Damage	Delays in service		
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Changes to Climate	Increased air temperature	Increased spread of vector borne diseases	More checks required	Delays in service			
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Changes to Ocean Temperature	Accelerated algal growth	Decreased dissolved oxygen	Habitat alteration	Decreased biodiversity	Novel challenges with new ecosystem	Delays in service	
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Habitat alteration	Spread of INNS	Delays in service				
Low Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Temperatures	Accumulation of ice / snow on surfaces	Decreased traction of surfaces	Increased risk of slips/trips	Increased danger of traveling	Health risks to staff	Delays in service	
Low Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Temperatures	Accumulation of ice / snow on surfaces	Increased use of cold weather supplies i.e. grit/heating fuel	Deficiency in cold weather supplies.	Delays in service			

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Drought	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Rainfall	Decreased river flow	Reduced lock operation	Limitation on number of vessels	Delays in service			
Drought	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Rainfall	Decreased river flow	Decreased propellor efficiency	Increased fuel consumption	Delays in service			
Drought	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Rainfall	Decreased river flow	Reduced river depth	Reduction in maximum vessel cargo capacity	Impact on inland waterway transport	Delays in service		
Drought	DfT Climate Risk Assessment Guidance for the Transport Sector	Low Rainfall	Decrease in water availability	Decreased vessel movement capacity	Inhibition for port activities	Delays in service			
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Pluvial Flooding	Inundation of site	Inundation of structural assets	Damage to structures	Damage	Delays in service	
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Increased runoff	Increased concentration of pollutants and nutrients	Contamination of potable water supply	Delays in service			
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Increased runoff	Litter entering watercourses	Distribution of litter downstream	Delays in service			
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Fluvial Flooding	Accelerated deterioration of riverine structures	Damage	Delays in service			
Precipitation / Flooding	DfT Climate Risk Assessment Guidance for the Transport Sector	Intense rainfall	Fluvial Flooding	River Bank Erosion	Delays in service				
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Flooding	Disruption in supply chain	Supply issues for imported construction materials	Cessation of construction / maintenance	Delays in service			

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Flooding	Inundation of road network	Staff unable to reach port	Delays in service				
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Overheating of assets	Overheating of equipment	Failure of port machinery	Delays in service			
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Increase in leisure boating	Collisions with smaller craft	Delays in service				
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Habitat alteration	Spread of INNS	Delays in service				
High Temperature	DfT Climate Risk Assessment Guidance for the Transport Sector	High Temperatures	Overheating of assets	Overheating of equipment	Overheating of vessel engines	Failure of vessel engines	Stranded vessels	Delays in service	
Sea level rise	DfT Climate Risk Assessment Guidance for the Transport Sector	Sea Level Rise	Increased erosion / deposition / submergence	Restricted access to port areas	Maintenance issues	Interruption of port operations	Delays in service		
Sea level rise	DfT Climate Risk Assessment Guidance for the Transport Sector	Sea Level Rise	Increased erosion / deposition / submergence	Changes in bathymetry	Compromised / Unreliable telemetry configurations	Delays in service			
Sea level rise	DfT Climate Risk Assessment Guidance for the Transport Sector	Sea Level Rise	Increased erosion / deposition / submergence	Changes in bathymetry	Natural infill of dredged areas	Increased frequency of dredging	Delays in service		
Sea level rise	DfT Climate Risk Assessment Guidance for the Transport Sector	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Damage to port structures	Damage to buildings	Damage	Delays in service	
Sea level rise	DfT Climate Risk Assessment Guidance for the Transport Sector	Sea Level Rise	Coastal squeeze	Habitat loss	Species Migration	Delays in service			

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Sea level rise	DfT Climate Risk Assessment Guidance for the Transport Sector	Sea Level Rise	Reduced bridge clearance	Decreased accessibility of waterways	Navigational / timeframe challenges	Delays in service			
Sea level rise	DfT Climate Risk Assessment Guidance for the Transport Sector	Sea Level Rise	Increased wave agitation	Increased water pressure on lock gates	Uncontrolled opening	Damage	Delays in service		
Sea level rise	DfT Climate Risk Assessment Guidance for the Transport Sector	Sea Level Rise	Overtopping of coastal defences	Interruption of port operations	Closure of port	Delays in service			
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Powerful Storm Event	Increased wave height	Overtopping of coastal defences	Damage to harbour authority assets	Damage to electrical equipment	Damage	Delays in service	
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Frequency of Extreme Weather Events	Cessation of contractual work	Delays in service					
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Powerful Storm Event	High windspeed	Reduction or interruption of operation	Delays in service				
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Powerful Storm Event	Increased wave height	Damage to telemetry systems	Damage				
Storms	DfT Climate Risk Assessment Guidance for the Transport Sector	Powerful Storm Event	Increased wave height	Disruption to operations	Delays in service				
Sea level rise	Transport system resilience: Summary and Conclusions (International Transport Forum - ITF)	Sea Level Rise	Reduced bridge clearance	Decreased accessibility of waterways	Navigational / timeframe challenges	Delays in service			
Precipitation / Flooding	British Ports Association: Climate change	Intense rainfall	Increased runoff	Pluvial flooding	Delays in service				

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
	and ports Impacts and adaptation strategies								
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	High Temperatures	Decreased river flow	Reduced vessel / river bank clearance	Reduced vessel carrying capacity	Delays to service			
Sea level rise	TACTRAN: Climate Change Adaptation Policy Statement	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Damage to port structures	Delays in service			
Sea level rise	Peel Ports Group Climate Change Adaptation Report	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Delays in service				
Sea level rise	Peel Ports Group Climate Change Adaptation Report	Sea Level Rise	Increased erosion / deposition / submergence	Damage to protected habitats	Delays in service				Monitoring physical damage to protected habitats
Sea level rise	Peel Ports Group Climate Change Adaptation Report	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Disruption of navigation	Disruptions to loading / offloading processes	Delays in service		Monitoring water quality parameters (including water chemistry) Water level > 10.1m OD for Liverpool.
Sea level rise	British Ports Association: Climate change and ports Impacts and adaptation strategies	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Delays in service				Projected sea level rise (2100)
Sea level rise	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Reduced services	Disrupted schedules	Delays in service		Disruption to shipping times of perishable goods / Disruption to passenger wait times.

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Sea level rise	ABP ARP3 Report	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Cessation of operations	Delays in service			Flood damage of harbour authority assets
Oceanic Warming	British Ports Association: Climate change and ports Impacts and adaptation strategies	Changes to Ocean Temperature	Accelerated algal growth	Increased biofouling of maritime assets	Damage	Delays in service			
Marine currents	British Ports Association: Climate change and ports Impacts and adaptation strategies	Changes to Marine Currents	Changed hydrographical conditions	Changes to patterns of sedimentation	Increased dredging / disposal requirements	Delays in service			
Storms	Peel Ports Group Climate Change Adaptation Report	Powerful Storm Event	Increased wave height	Overtopping of coastal defences	Structural damage	Damage	Delays in service		Condition of Bollards (Regular condition audits of bollards)
Storms	Port of Dover ARP3 Report	Powerful Storm Event	Increased wave height	Overtopping of coastal defences	Inundation of quaysides	Overspill into surrounding area	Damage	Delays in service	Flooding thresholds: Storm surge >8m: Flooding to car parks around marina DTM Models: Created for 8, 8.5 and 9.5m storm surge events. Historical data: Historical data held for storm surges e.g. St. Jude storm 2013, which caused damage to the port.
Storms	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change	Powerful Storm Event	Increased wave height	Overtopping of coastal defences	Damage to port infrastructure	Damage	Delays in service		

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
	Research Program)								
Storms	British Ports Association: Climate change and ports Impacts and adaptation strategies	Powerful Storm Event	Increased wave height	Overtopping of coastal defences	Inundation of port infrastructure	Damage	Delays in service		
Storms	ABP ARP3 Report	Powerful Storm Event	High windspeed	Damage to structures	Damage	Delays in service			Asset surveys and maintenance costs
Storms	Peel Ports Group Climate Change Adaptation Report	Powerful Storm Event	Increased wave height	Reduced ability to board pilots	Delays in service				Trends in wave height exceedance
Storms	ABP ARP3 Report	Powerful Storm Event	High windspeed	Exceedance of safe operation conditions	Reduction or interruption of operation	Delays in service			Vessel delay
High Temperature	Port of London Authority ARP3 Report	Changes to Climate	Migration of INNS	Novel species interactions	Greater spread of pandemics	Delays in service			
Storms	British Ports Association: Climate change and ports Impacts and adaptation strategies	Powerful Storm Event	Increased wave height	Increased penetration of waves into harbours	Changed sediment transport / Deposition	Altered positions of sand/mud banks	Navigational Challenges	Delays in service	Projected changes in average and extreme wave heights.
Storms	British Ports Association: Climate change and ports Impacts and adaptation strategies	High Windspeed	Increased stress on infrastructure	Damage	Delays in service				
Weather Extremes	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Intense rainfall	Pluvial Flooding	Inundation of rail network	Cancellations	Delays in service			Cancellations and significant lateness (CaSL): Number and percentage of passenger trains which are cancelled, or which arrive 30 or more minutes later than time

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
									shown in timetable. (Network Rail)
High Temperature	Transport system resilience: Summary and Conclusions (International Transport Forum - ITF)	High Temperatures	Overheating of assets	Overheating of equipment	Thermal expansion of bridges/joints	Rail buckling	Damage to machinery and engines	Delays in service	Measuring recovery time and Network connectivity as a measure of resilience
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	High Temperatures	Environmental Transformation	Dehydration of Green Infrastructure	Decreased soil stability	Ground Movement	Changed track geometry and integrity	Delays in service	
Sea level rise	TFL adaptation reporting power 3	Sea Level Rise	Overtopping of coastal defences	Coastal water ingress	Asset failure	Delays in service			Projections: UKCP projected change in sea level by late 21st Century.
Drought	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	Low Rainfall	Low soil moisture	Decreased stability of slopes	Landslides	Delays in service			
High Temperature	HS2 Climate Adaptation ARP Report	High Temperatures	Overheating of assets	Overheating of equipment	Thermal expansion of bridges/joints	Damage to bridge structures	Damage		
High Temperature	HS2 Climate Adaptation ARP Report	High Temperatures	Overheating of assets	Overheating of equipment	Failure of overhead line equipment (OLE)	Reduction in electrical loading capability	Operations failures	Delays in service	
High Temperature	HS2 Climate Adaptation ARP Report	High Temperatures	Dehydration of Green Infrastructure	Ignition of green infrastructure	Damage	Delays in service			"Number of extremely hot days"
High Temperature	TFL adaptation reporting power 3	High Temperatures	Exceedance of max. working temperature	Heat-related illnesses	Delays in service				(Met office): Number of hot days (30°C+, 35°C+) AND hot

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
									spells (3+ days) per year
Weather Extremes	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Frequency of Extreme Weather Events	Increased wear on road surface	Increased incidence of engineering works	Increased number of works-related disruptions	Delays in service			Passenger disruption index (PDI): Measures extent of planned disruption to passenger services caused by engineering works on the network.
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	High Temperatures	Exposure of flammable materials to heat	Ignition of flammable materials	Fire	Damage			
Precipitation / Flooding	Climate Change Adaptation and Transport Infrastructure NatCen	Intense rainfall	Pluvial Flooding	Inundation of Bridges	Increased scour of bridges	Damage to structures	Increased requirement for maintenance	Delays in service	
Precipitation / Flooding	Network Rail Third Adaptation Report December 2021 AND NETWORK RAIL APPENDIX A integrated ARP3 climate risk assessment	Intense rainfall	Overwhelming of drainage systems	Pluvial Flooding	Inundation of site	Inundation of sub-structures	Erosion of tunnels through spalling	Damage	Assessment of current drainage management practices
Precipitation / Flooding	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	Intense rainfall	Exceedance of drainage capacity	Pluvial Flooding	Closure of rail network	Delays in service			
Snowfall	Network Rail Third Adaptation Report December	Low Temperatures	Increased frequency of	Increased wear on geotechnical assets	Damage	Delays in service			Cost of cold weather impacts (2006-2021)

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
	2021 AND NETWORK RAIL APPENDIX A integrated ARP3 climate risk assessment		freeze - thaw cycles						
High Temperature	TfNSW (Transport for New South Wales) Climate Risk Assessment Guidelines	High Temperatures	Exceedance of max. working temperature	Solar exposure of staff	Heat-related illnesses	Delays in service			Number of extreme heat days
High Temperature	TFL adaptation reporting power 3	High Temperatures	Exceedance of max. working temperature	Heat-related illnesses	Delays in service				Projections: UKCP probabilistic projections of extreme temperatures (hot days >30 / 35c)
High Temperature	European Climate Risk Assessment	High Temperatures	Overheating of assets	Overheating of equipment	Overheating of rails	Rail buckling	Rail breakages	Delays in service	Projection: Damage from heatwaves projected to account for 92% of total damage by 2080 (especially roads and rail due to blow ups).
Precipitation / Flooding	TFL adaptation reporting power 3	Intense rainfall	Increase in groundwater level	Exceedance of infrastructure saturation limit	Asset failure	Damage	Delays in service		Surface Asset Management Information System (SAMIS) - used in SuDS management.
Precipitation / Flooding	HS2 Climate Adaptation ARP Report	Intense rainfall	Landslides	Damage	Delays in service				Vegetation standards: Monitored and of importance for soil stability.
Precipitation / Flooding	TFL adaptation reporting power 3	Intense rainfall	Pluvial Flooding	Inundation of site	Damage to building assets and trains	Decreases in surface grip	Safety risk (slips/falls, unsafe structures)	Delays in service	Projections: Rainfall percentage uplifts from 'Future

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
									Drainage' project (increases in capacity)
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	High Temperatures	Overheating of assets	Overheating of equipment	Failure of overhead line equipment (OLE)	Reduced train speeds	Delays in service		
High Temperature	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	High Temperatures	Overheating of assets	Overheating of equipment	Overheating of rails	Rail buckling	Damage	Delays in service	Number of track buckles: Record of number of failures of track through buckling during a specific period.
High Temperature	Climate Change Adaptation and Transport Infrastructure NatCen	High Temperatures	Overheating of assets	Overheating of equipment	Overheating of tracks	Track buckling	Misalignment of track	Derailment	
High Temperature	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	High Temperatures	Overheating of assets	Overheating of equipment	Overheating of rails	Rail buckling	Rail breakages	Delays in service	
Storms	TFL adaptation reporting power 3	High Windspeed	Damage to local tress / leaf fall	Dislodging of debris	Blockage / damage to network	Delays in service			
Storms	Climate Change Adaptation and Transport Infrastructure NatCen	High Windspeed	Dislodging of debris	Obstruction on track	Delays in service				
High Temperature	TfNSW (Transport for New South Wales) Climate Risk Assessment Guidelines	Increased Humidity	Saturation of electrical equipment	Damage to electrical equipment	Failures of electrical equipment	Delays in service			Level of engineered redundancy

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Precipitation / Flooding	TfNSW (Transport for New South Wales) Climate Risk Assessment Guidelines	Intense rainfall	Increased runoff	Pluvial Flooding	Inundation of structural assets	Delays in service			2070 precipitation projections
Sea level rise	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Sea Level Rise	Overtopping of coastal defences	Inundation of site	Damage to port structures	Damage	Delays in service		CERDS at risk of coastal surge: Length or number of coastal and estuarine rail defences subject to wave and storm action.
Storms	HS2 Climate Adaptation ARP Report	High Windspeed	Increased stress on infrastructure	Damage	Delays in service				
Precipitation / Flooding	Network Rail Third Adaptation Report December 2021 AND NETWORK RAIL APPENDIX A integrated ARP3 climate risk assessment	Intense rainfall	Pluvial Flooding	Inundation of site	Inundation of rail network	Damage to tracks	Damage	Delays in service	Total costs associated with precipitation (2006-2021)
High Temperature	Network Rail Third Adaptation Report December 2021 AND NETWORK RAIL APPENDIX A integrated ARP3 climate risk assessment	High Temperatures	Dehydration of Green Infrastructure	Clay shrinkage of embankments	Deterioration of track geometry	Performance impacts	Delays in service		Cost of hot weather impacts Total delay time due to hot weather impacts
Drought	HS2 Climate Adaptation ARP Report	Low Rainfall	Low soil moisture	Soil cracking and subsidence	Movement of overhead line equipment (OLE)	Damage	Delays in service		
Snowfall	TFL adaptation reporting power 3	Snowfall	Build up of snow and ice on tracks	Decreased grip for cars	Decreased control of vehicles	Delays in service			Projections: Number of Air Frost days/snow days per year

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Low Temperature	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Low Temperatures	Increased frequency of freeze - thaw cycles	Thermal contraction of rails	Increased number of rail faults	Increased maintenance on rail	Delays in service		Number of broken rails: Count of number of times broken rails occur on running lines (sidings and depots are excluded).
Low Temperature	HS2 Climate Adaptation ARP Report	Low Temperatures	Increased frequency of freeze - thaw cycles	Thermal contraction of rails	Increased risk of rail breaks	Damage	Delays in service		
High Temperature	European Climate Risk Assessment	High Temperatures	Environmental Transformation	Permafrost melt	Decreased soil stability	Degradation of slope stability	Impacts on structural integrity of ropeway transport infrastructure	Delays in service	
Precipitation / Flooding	Network Rail Third Adaptation Report December 2021 AND NETWORK RAIL APPENDIX A integrated ARP3 climate risk assessment	Intense rainfall	Increase in groundwater level	Exceedance of infrastructure saturation limit	Damage	Delays in service			Number of failures and incidents related to overhead line equipment (OLE) systems
Drought	TFL adaptation reporting power 3	Low Rainfall	Low soil moisture	Earthworks failures	Decreased stability of slopes	Damage	Delays in service		Projections: UKCP probabilistic projections of climate extremes.
Snowfall	HS2 Climate Adaptation ARP Report	Snowfall	Overloading of overhead line equipment (OLE)	Sensitive equipment failure	Damage	Delays in service			
Storms	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	Powerful Storm Event	Increased wave height	Overtopping of coastal defences	Coastal water ingress	Slope failure	Blockage of rail network	Delays in service	

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Storms	Network Rail Third Adaptation Report December 2021 AND NETWORK RAIL APPENDIX A integrated ARP3 climate risk assessment	Powerful Storm Event	Increased wave height	Erosion of coastal defences	Overtopping of coastal defences	Surface water flooding	Delays in service		
Storms	TfNSW (Transport for New South Wales) Climate Risk Assessment Guidelines	High Windspeed	Increased stress on infrastructure	Damage to ICT infrastructure	Interruptions to communication networks	Delays in service			
Storms	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	Intense rainfall	Pluvial Flooding	Earthworks failures	Landslides	Damage			
Temperature Extremes	Network Rail Third Adaptation Report December 2021 AND NETWORK RAIL APPENDIX A integrated ARP3 climate risk assessment	High Temperatures	Environmental Transformation	Increase shrink-swell cycles	Damage				Total costs associated with heat (2006-2021)
Precipitation / Flooding	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Intense rainfall	Exceedance of drainage capacity	Pluvial Flooding	Inundation of rail network	Decreased adhesion between track and train	Station overruns	Delays in service	Station over-runs: Event in which a train proceeds beyond the designated stopping point. (Network Rail)
Drought	TFL adaptation reporting power 3	High Temperatures	Dehydration of Green Infrastructure	Ignition of green infrastructure	Wildfires	Damage to infrastructure	Damage		Projections: UKCP probabilistic projections of extreme

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
									temperatures (hot days >30 / 35c)
Climate change	Office of Rail and Road ARP4	Intense rainfall	Pluvial Flooding	Inundation of rail network	Damage to building assets and trains				Delay Attribution Service: Impact of weather on bridges / earthworks) (sub-category)
Precipitation / Flooding	Office of Rail and Road ARP4	Intense rainfall	Inundation of site	Transport of debris	Debris on track	Decreases in surface grip	Delays in service		Delay Attribution Service: Low adhesion between wheels and track (sub-category)
Climate change	Office of Rail and Road ARP4	Impact chain route not sufficiently explicit within source report							Delay Attribution Service: Weather impacting network operations (sub-category)
Climate change	Office of Rail and Road ARP4	Impact chain route not sufficiently explicit within source report							Delay Attribution Service: Severe weather beyond design capability of infrastructure (sub-category)
Storms	Office of Rail and Road ARP4	High Windspeed	Dislodging of debris	Transport of debris	Obstruction on track	Delays to service			Delay Attribution Service: Track circuit failures due to leaf fall. (sub-category)
Storms	Office of Rail and Road ARP4	High Windspeed	Dislodging of debris	Transport of debris	Obstruction on track	Delays to service			Delay Attribution Service: Wheel slip due to leaf fall (sub-category)
Climate change	Office of Rail and Road ARP4	Frequency of Extreme Weather Events	Inundation of track	Obstruction of track	Delays in service				Train stranding due to extreme weather
Precipitation / Flooding	Climate Change Committee: CCRA4 Template I6	Intense rainfall	Inundation of rail network	Transport of debris	Debris on track	Decreases in surface grip	Derailment	Delays in service	
High Temperature	Climate Change Committee:	High Temperatures	Overheating of assets	Overheating of rails	Rail buckling	Rail breakages	Delays in service		At a temperature of 26°C and

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
	CCRA4 Template I6								above, the number of faults increased with an increase in temperature: for each 1°C rise in temperature, the number of power system faults increased by 2.4 and the number of railway fault events increased by 2
Storms	Climate Change Committee: CCRA4 Template I6	Powerful Storm Event	High windspeed	Transport of debris	Damage	Delays in service			
Storms	Climate Change Committee: CCRA4 Template I6	Powerful Storm Event	High windspeed	Exceedance of safe operation conditions	Reduction or interruption of operation	Delays in service			
Low temperature	Climate Change Committee: CCRA4 Template I6	Low Temperatures	Increased reliance on heating equipment	Increased impact of energy deficiencies	Delays in service				Temperature thresholds below 7°C: for each 1°C decrease in temperature, the number of power system faults increased by 2.1 and the number of railway system faults increased by 6.1
Climate change	Climate Change Committee: CCRA4 Template I6	Frequency of Extreme Weather Events	Rapidly changing temperatures	Increased wear on rail	Damage	Delays in service			Soil pore pressures is identified as the key parameter for determining earthwork asset stability
Weather Extremes	RSSB: Task 3AB Metrics Spreadsheet	Frequency of Extreme Weather Events	Decrease in vehicle control	Increase in collisions	Delays in service				Proportion of driver journeys delayed due to traffic congestion:

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
	(Compendium of metrics)								Measures the percentage of driver journeys delayed due to traffic congestion. (Transport Scotland)
Storms	Transport system resilience: Summary and Conclusions (International Transport Forum - ITF)	High Windspeed	Damage to local tress / leaf fall	Dislodging of debris	Damage to roadside assets	Obstruction of roads	Disruptions to traffic	Delays in service	
Sea level rise	Transport system resilience: Summary and Conclusions (International Transport Forum - ITF)	High Windspeed	Damage to local tress / leaf fall	Obstruction on track	Damage	Delays in service			
Low Temperature	National Highways ARP3 Report	Low Temperatures	Accumulation of ice / snow on surfaces	Increase shrink-swell cycles	Increasing rate of pavement deterioration	Damage	Delays in service		
Drought	Queensland Government: Climate Change and Natural Hazards Risk Assessment Guideline	Low Rainfall	Decrease in water availability	Increased difficulty with road maintenance	Delays in service				
Drought	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	Low Rainfall	Low soil moisture	Sinkholes	Damage	Increased maintenance requirements	Delays in service		
Temperature Extremes	Climate Change Adaptation and Transport Infrastructure NatCen	High Temperatures	Deteriorations in road user comfort	Delays in service					

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Low Temperature	National Highways ARP3 Report	Low Temperatures	Increased frequency of freeze - thaw cycles	Increased wear on geotechnical assets	Destabilisation of geotechnical / drainage assets	Damage	Delays in service		
Precipitation / Flooding	Queensland Government: Climate Change and Natural Hazards Risk Assessment Guideline	Intense rainfall	Exceedance of drainage capacity	Pluvial flooding	Inundation of road network	Increased risk of collision	Damage	Delays in service	
Low Temperature	TACTRAN: Climate Change Adaptation Policy Statement	Low Temperatures	Accumulation of ice / snow on surfaces	Formation of ice on roads	Decreased traction of surfaces	Decreased driving speed	Increased risk of accident	Increased danger of traveling	
Weather Extremes	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Frequency of Extreme Weather Events	Increased wear on road surface	Premature degradation of road surfaces	Damage	Increased incidence of engineering works	Delays in service		Road Quality: Surface Condition Index (Ministry of Transport New Zealand).
Weather Extremes	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Frequency of Extreme Weather Events	Dangerous driving conditions	Increase in road fatalities	Delays in service				Annual road fatalities: Annual road fatalities on the Highways Agency's motorway and A road network. (Highways Agency)
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	High Temperatures	Exposure of flammable materials to heat	Ignition of flammable materials	Fires	Reductions in visibility/road obstruction	Road closures	Delays in service	
Precipitation / Flooding	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	Intense rainfall	Pluvial flooding	Inundation of road network	Disruption to public and private transport	Delays in service			Direct costs of repairs to highways and other infrastructure from 2013-14 floods was £4 million

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
High Temperature	European Climate Risk Assessment	High Temperatures	Overheating of assets	Overheating of roads	Softening of road asphalt	Degradation in quality of roads	Damage	Delays in service	Costs associated with weather-induced hazards (projected EUR 10 billion (20x increase from current level)
High Temperature	Queensland Government: Climate Change and Natural Hazards Risk Assessment Guideline	High Temperatures	Dehydration of Green Infrastructure	Ignition of green infrastructure	Fire damage to equipment	Damage	Delays in service		
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	High Temperatures	Environmental Transformation	Permafrost melt	Rapid temperature change of road surface	Cracking / buckling and rutting from heat	Increased maintenance frequency	Delays in service	
High Temperature	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	High Temperatures	Overheating of assets	Overheating of roads	Thermal degradation of road surfaces	Delays in service			Economic effect, especially impact on delivery of perishable goods.
Storms	Climate Change Risk and Impact Assessment for Kent and Medway. Part 2: Transport Sector Summary	High Windspeed	Dislodging of debris	Obstruction of roads	Delays in service				
Storms	Climate Change Adaptation and Transport Infrastructure NatCen	High Windspeed	Toppling of high-sided vehicles	Obstruction of roads	Delays in service				
Precipitation / Flooding	National Highways ARP3 Report	Intense rainfall	Increase in ground saturation	Decreased ground stability	Earthworks failures	Landslides	Damage	Delays in service	

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
High Temperature	Queensland Government: Climate Change and Natural Hazards Risk Assessment Guideline	High Temperatures	Dehydration of Green Infrastructure	Ignition of green infrastructure	Damage	Delays in service			Number of hot days >35c
Precipitation / Flooding	National Highways ARP3 Report	Intense rainfall	Fluvial flooding	Surface water flooding	Inundation of site	Inundation of roads and access	Delays in service		Measurement of mitigation measures: No. Properties protected from flooding due to resilience building. Incident records: Drainage Data Management system, which records location and condition of assets / flooding incidents.
High Temperature	National Highways ARP3 Report	High Temperatures	Overheating of assets	Overheating of roads	Overexpansion / deforming of concrete	Increased risk of concrete 'blow-ups'	Damage	Delays in service	Monitoring - Monitoring of performance and temperature of current surfacing material of choice (thin surface course systems).
Precipitation / Flooding	National Highways ARP3 Report	Intense rainfall	Pluvial flooding	Inundation of site	Inundation of road network	Damage to roads	Damage	Delays in service	
High Temperature	TACTRAN: Climate Change Adaptation Policy Statement	High Temperatures	Overheating of assets	Overheating of roads	Thermal degradation of road surfaces	Increased road surface damage	Degradation in quality of roads	Damage	Spend on maintenance of asphalt/bituminous road surfaces
High Temperature	TACTRAN: Climate Change Adaptation Policy Statement	High Temperatures	Overheating of assets	Overheating of roads	Thermal degradation of road surfaces	Degradation in quality of roads	Damage	Delays in service	Spend on maintenance of asphalt/bituminous road surfaces

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Storms	National Highways ARP3 Report	High Windspeed	Increased scour	Damage to assets / signage	Damage	Delays to service			
Weather Extremes	TACTRAN: Climate Change Adaptation Policy Statement	Frequency of Extreme Weather Events	Disruption of road corridors	Delays in service					Days per year with severe traffic restrictions due to landslides in road sections (outcome indicator).
Snowfall	RSSB: Tomorrow's Railway and Climate Change Adaptation: Final Report, Task 3: Metrics evaluation appendices	Snowfall	Freeze-thaw cycles	Increase wear on roads	Decreased grip for cars	Increased risk of accident	Delays in service		Tonnes of salt used in winter maintenance Weather incidents with snow and drifting snow
Low Temperature	European Climate Risk Assessment	Frequency of Extreme Weather Events	Rapidly changing temperatures	Increased wear on road surface	Damage	Delays in service			
High Temperature	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	Low Rainfall	Decrease in water availability	Increased groundwater pumping	Subsidence of soils	Reduced slope stability	Reduced Pavement Stability	Damage	
Snowfall	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Snowfall	Decreased grip for cars	Decreased control of vehicles	Increased risk of accident	Delays in service			Weather incidents with snow and drifting snow (Trafikverket - Swedish Transport Administration).
Snowfall	RSSB: Task 3AB Metrics Spreadsheet (Compendium of metrics)	Snowfall	Increased use of salt on roads	Increase wear on roads	Increased requirements for maintenance	Delays in service			Tonnes of Salt used in winter maintenance (Norwegian Public Roads Administration)
Precipitation / Flooding	Transport system resilience: Summary and	Intense rainfall	Increase in groundwater level	Subsidence of substrata	Decreased structural stability of bridges	Failure of bridges	Damage	Delays in service	

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
	Conclusions (International Transport Forum - ITF)								
Precipitation / Flooding	TACTRAN: Climate Change Adaptation Policy Statement	Intense rainfall	Pluvial flooding	Inundation of road network	Delays in service				Estimated days per year of avoided weather-related disruption to the relevant road network section.
Storms	US Climate Resilience Toolkit NCA5 Ch13 transportation (US Global Change Research Program)	Powerful Storm Event	Pluvial Flooding	Increased soil saturation	Landslides	Blockage of travel lanes and bus routes	Delays in service		
Low temperature	Climate Change Committee: CCRA4 Template I5	Low Temperatures	Accumulation of ice / snow on surfaces	Increased number of road faults	Increased danger of traveling	Damage	Delays in service		Consequential economic impact of delay
High Temperature	Climate Change Committee: CCRA4 Template I5	High Temperatures	Dehydration of Green Infrastructure	Ignition of green infrastructure	Wildfires	Reductions in visibility/road obstruction	Increased frequency of traffic collisions	Delays in service	
Precipitation / Flooding	Climate Change Committee: CCRA4 Template I5	Intense rainfall	Saturation of ground	Destabilisation of ground	Landslides	Damage	Delays in service		Average rainfall intensity was 11 mm/h with a peak of 21.8 mm/h.
Precipitation / Flooding	Climate Change Committee: CCRA4 Template I5	Intense rainfall	Pluvial Flooding	Transport of debris	Damage	Delays in service			
Precipitation / Flooding	Climate Change Committee: CCRA4 Template I5	Intense rainfall	Pluvial Flooding	Inundation of road network	Damage to roads	Damage	Delays in service		
Low temperature	Climate Change Committee: CCRA4 Template I5	Low Temperatures	Accumulation of ice / snow on surfaces	Increased risk of slips/trips	Increased danger of traveling	Health risks to staff	Delays in service		

Hazard Category	Source	Chain 1	Chain 2	Chain 3	Chain 4	Chain 5	Chain 6	Chain 7	Metric
Precipitation / Flooding	Climate Change Committee: CCRA4 Template I5	Intense rainfall	Pluvial Flooding	Inundation of road network	Transport of debris	Damage to roads	Damage	Delays in service	

Appendix 3: Stakeholders Engaged

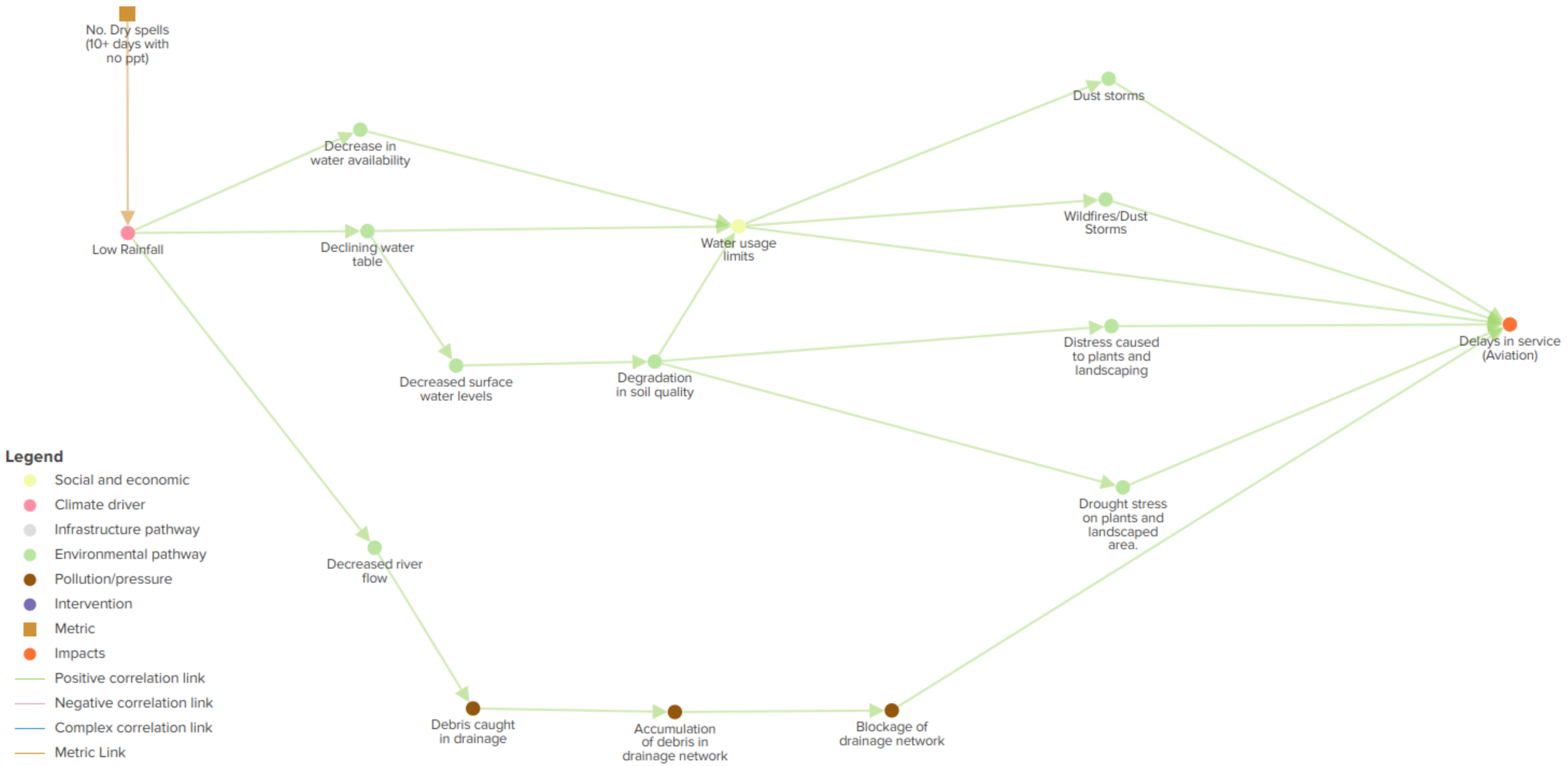
Appendix 3 lists the organisations engaged through the WS1 workshop.

- Association of Directors of Environment, Economy, Planning & Transport (ADEPT)
- British Aviation Group
- British Ports Association
- Civil Aviation Authority
- Climate Change Committee
- Defra
- Decarbonised, Adaptable and Resilient Transport Infrastructures (DARe Hub)
- East West Rail
- High Speed 1
- High Speed 2
- Hutchison Ports
- Manchester Airports Group
- Met Office
- National Infrastructure Commission
- National Highways
- National Air Traffic Services (NATS)
- Network Rail
- Office of Rail and Road
- Port of London
- Rail Safety and Standards Board (RSSB)
- Susteer
- Transport for Greater Manchester
- Transport for London
- Transport for West Midlands
- UK Roads Leadership Group (UKRLG)
- West Midlands Combined Authority
- Department for Transport

Appendix 4: Systems thinking mapping

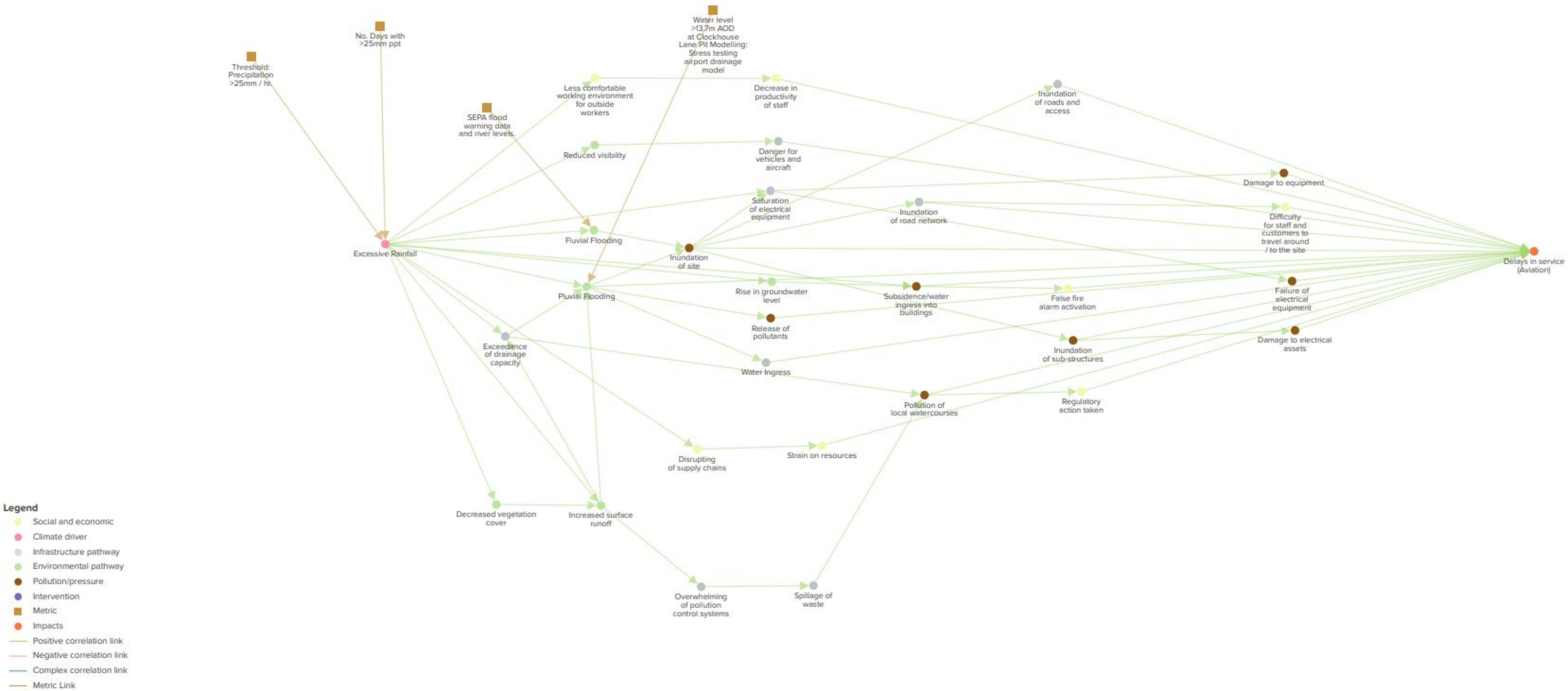
Appendix 4 presents extract of systems thinking mapping exports.

Figure 7.1: Aviation: Drought systems thinking map



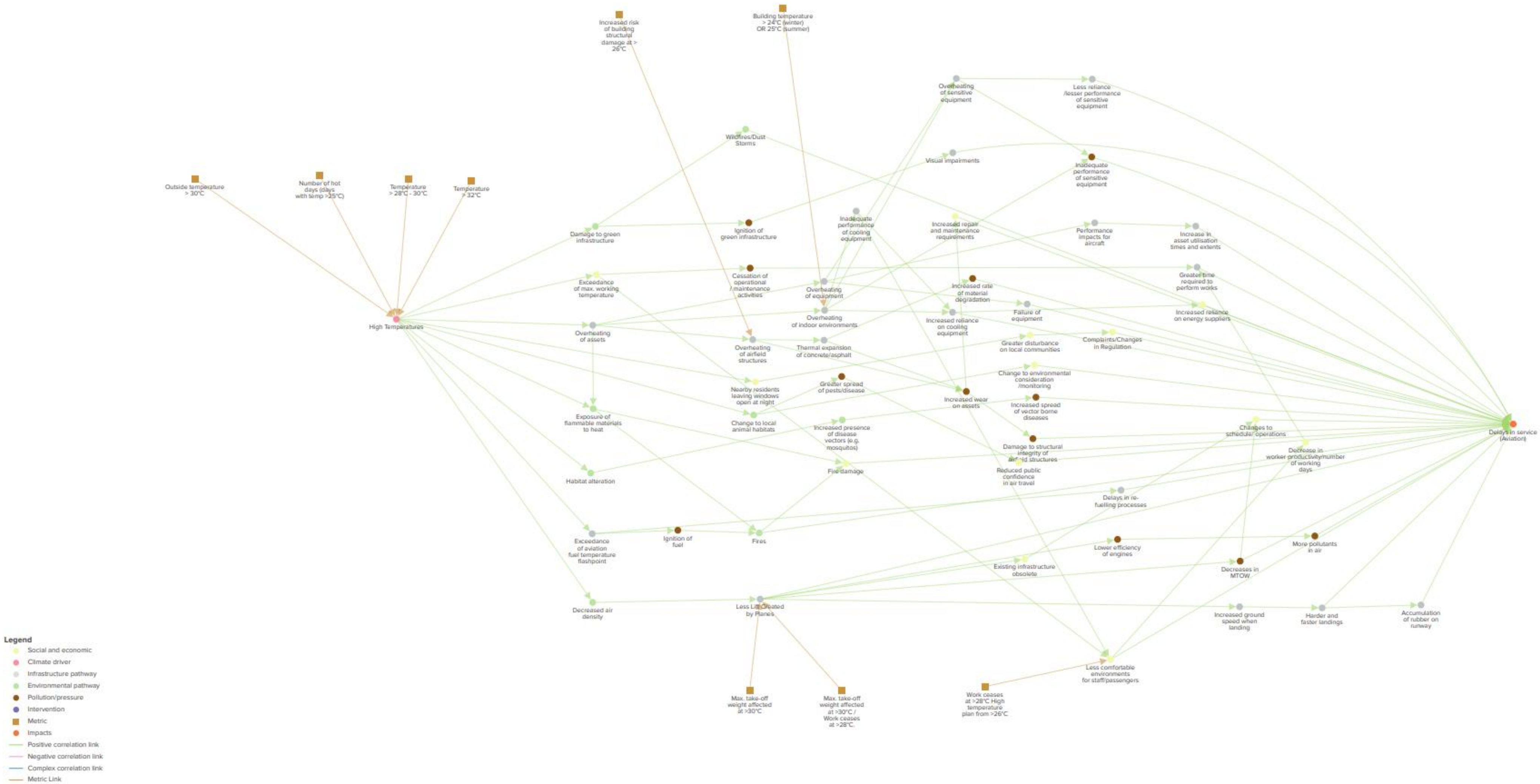
Source: Mott MacDonald analysis based on information collected through reviews of publicly available information and stakeholder engagement, 2025

Figure 7.2: Aviation: Heavy rainfall systems thinking map



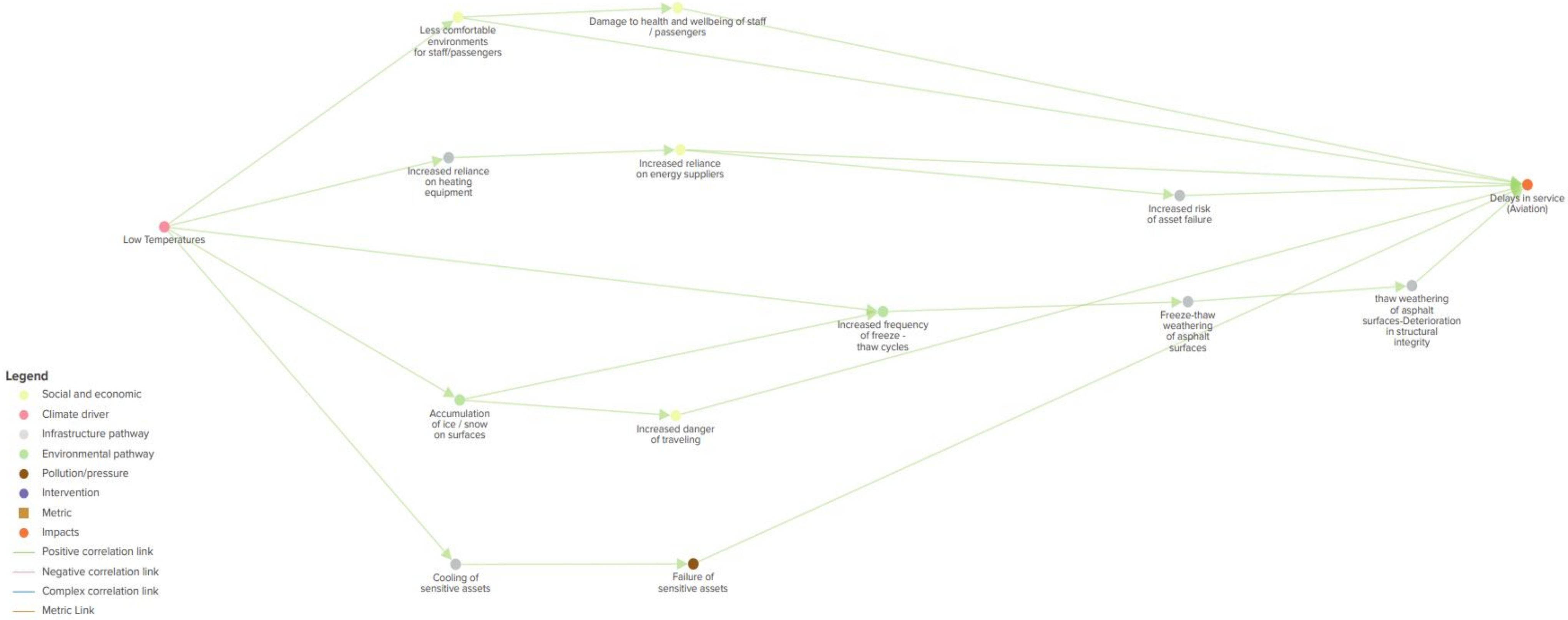
Source: Mott MacDonald analysis based on information collected through reviews of publicly available information and stakeholder engagement, 2025

Figure 7.3: Aviation: High temperatures system thinking map



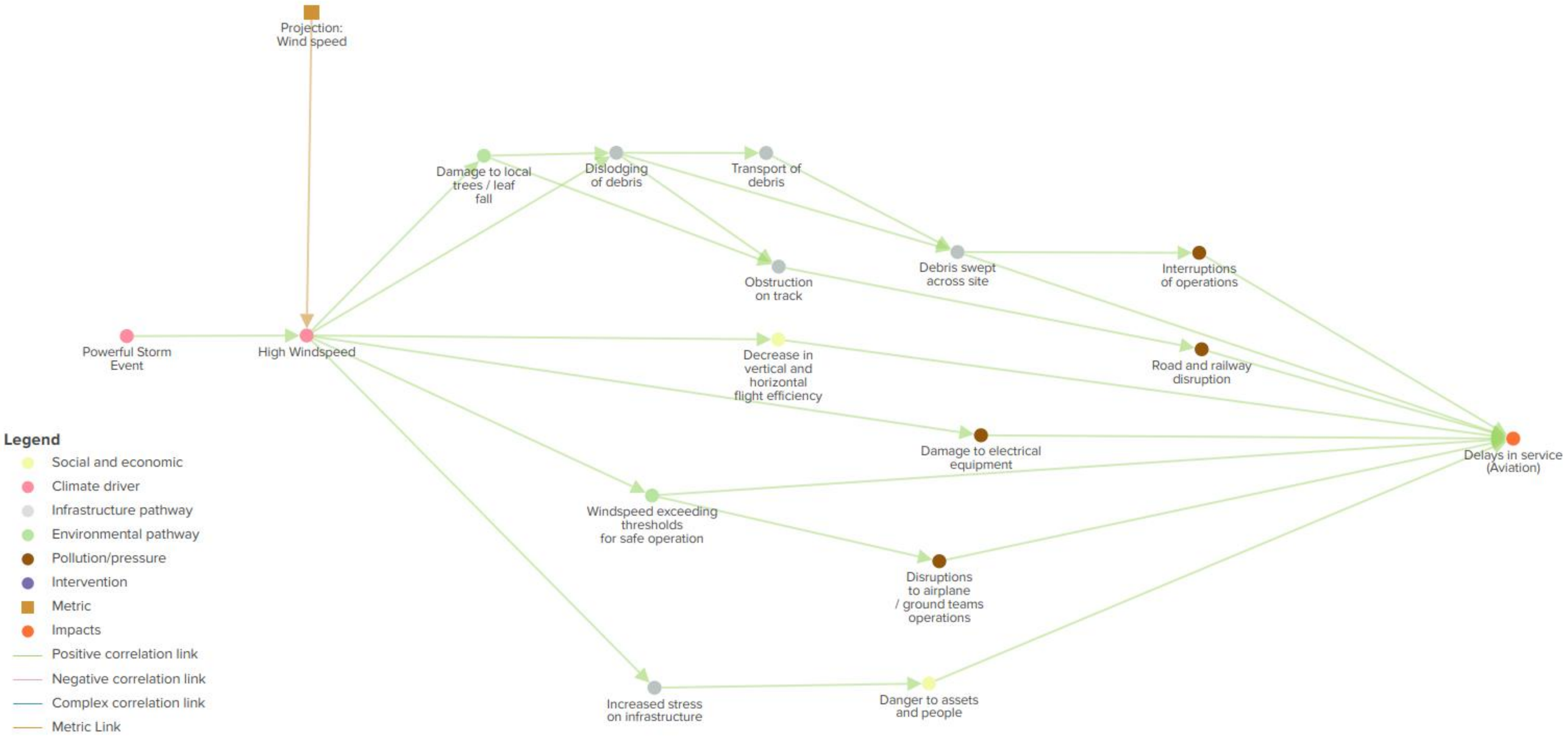
Source: Mott MacDonald analysis based on information collected through reviews of publicly available information and stakeholder engagement, 2025

Figure 7.4: Aviation: Low temperatures systems thinking map



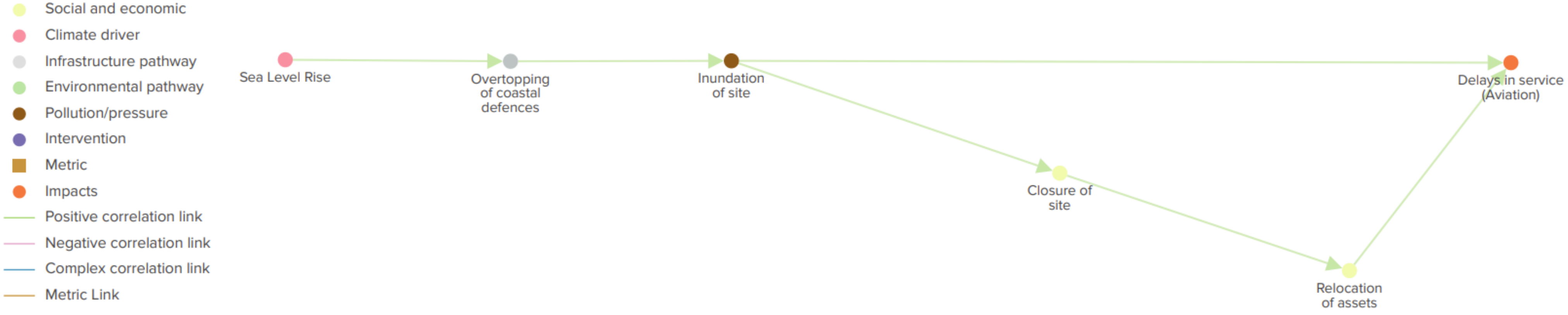
Source: Mott MacDonald analysis based on information collected through reviews of publicly available information and stakeholder engagement, 2025

Figure 7.5: Aviation: Storms and high windspeed systems thinking map



Source: Mott MacDonald analysis based on information collected through reviews of publicly available information and stakeholder engagement, 2025

Figure 7.6: Aviation: Sea level rise systems thinking map



Source: Mott MacDonald analysis based on information collected through reviews of publicly available information and stakeholder engagement, 2025