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Group of Experts on Assessment of Climate Change Impacts and Adaptation for Inland Transport

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Item 6 of the provisional agenda
Guidelines for integrating climate change considerations in planning and operational processes

Stress test framework

Note by the secretariat

I. Background

1. At its twenty-third session, the Group of Experts on Assessment of Climate Change Impacts and Adaptation for Inland Transport (GE.3) requested that the stress test framework is elaborated based on the annotated outline.

2. This document contains the draft stress test framework. It was elaborated by experts from Swiss Federal Institute of Technology in Zürich, Engineer Research and Development Center, USACE, National Centre for Atmospheric Research, Climate Sense and France.

3. GE.3 is invited to consider this draft framework and provide comments.

II. Stress test framework

A. Introduction

This stress testing framework builds upon the paper by Adey et al and provides practical guidance on how to apply one or more stress tests on transport systems. The functioning of society depends on the transportation of goods and persons and the infrastructure required to enable transportation is built to ensure that this can happen in specified ways – that is, built to provide specified levels of service.

As losses in service due to disruptive events (e.g., natural hazards such as floods, heavy snowfalls) can have significant societal consequences (chapter II.2), the transport infrastructure should be managed in such a way that the consequences of extreme events are minimised, taking into consideration their available resources and their potential return on investment. This framework (in chapter II.3 and II.4) shows how stress tests can be used to determine if an intervention program is needed to ensure transport infrastructure provides an adequate level of service in the context of climate change hazard.

Case studies (in chapter II.5) on road- and rail-networks illustrate the approach, giving real-life examples of application.

The stress test concept can be used as part of an assessment process that helps to identify impacts whilst formulating a plan for adaptation to climate change or to deal with other risks. ISO 14090:2019 Adaptation to climate change – Principles, requirements and guidelines is the benchmark standard for adaptation planning, and calls for impact assessments, which then are prioritised whereby plans are then drawn up to deal with these impacts. ISO 14090 does not mandate - require - any particular form of impact assessment; it requires an impact assessment, then goes on to say that this can be a risk assessment, a vulnerability assessment, or a thresholds analysis.

Stress tests provide another way of carrying out an impact analysis and as such, would comply with ISO 14090 requirements.

Stress tests are especially used to determine the resilience of the transport system in specific situations, by assessing how it will perform in these specific situations, i.e. will it be able to provide specified level of service for which it was built.

A stress test can provide valuable input into an adaptation plan that addresses many impacts within a transport system, potentially both as an early contribution to such a plan, and during the drafting of a more comprehensive adaptation plan. Part of the stress test may use risk or vulnerability assessments or thresholds analysis techniques.

B. Climate change hazards

1. Climate impact now

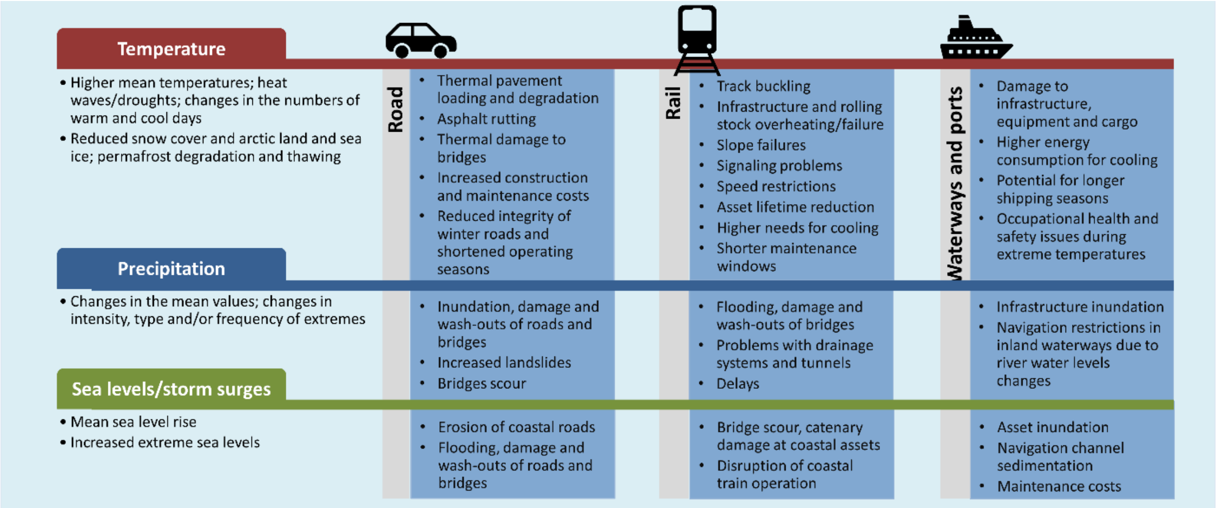
Globally, we face an existential climate crisis that threatens our ability to sustain safe, reliable, available, and equitable transportation services to the communities that need them. Adapting to future impacts of climate change is not a concern to be researched and decided upon later: it is an issue to be dealt with now. In fact, the World Economic Forum's Global Risk Report identifies the failure to create policy to address extreme weather and climate change as one of our greatest short to medium-term global threats (WEF 2019). The impacts of climate risk are being felt now, and we are presented with an unprecedented opportunity to understand those risks and prepare for them so that impacts can be reduced for our vulnerable communities.

In the most recent report written by the International Panel on Climate Change (IPCC AR6 2022), widespread and pervasive impacts have been observed in human and ecological systems due to increases in the frequency and intensity of climate and weather extremes. The IPCC report divides climate impacts and risks into several categories: observed, near-term (2021-2040), mid (2041-2060) and long-term (2081-2100). The magnitude and rate of projected climate change impacts in these categories depends on the near-term mitigation and adaptation actions to reduce emissions (i.e. Representative Concentration Pathways, IPCC AR6 2022). Regardless of any action there are a variety of adverse losses and damages to be expected, especially for small islands and megacities located in low-lying coastal areas (Monioudi et al. 2018; Storlazzi et al. 2018).

The U.S. Global Change Research Programs Fourth National Climate Assessment echoes the findings of IPCC AR6, mentioning that 'thousands of studies' have documented global changes in atmospheric, surface, and ocean temperature; diminishing sea ice, melting glaciers, rising sea levels, ocean acidification, and increasing water vapor (USGCRP 2018). These effects can be divided into two categories based on the impact they have on a system's intended functionality (e.g. safe and efficient travel). The first category includes chronic and long-term changes in weather patterns that stress a system into delivering its intended function at a new steady state. These climate hazards are defined as "stressors" and can include things like precipitation patterns, rises in temperature, sedimentation, sea level rise, and coastal erosion. The second category includes episodic disruptions that require a system to absorb and attempt to recover to its former functionality. These shorter-term events can often have major regional impacts that may be difficult to recover from or create lasting change. These disruptions include more commonly known climate extremes like riverine flooding, landslides, debris flows, ice phenomena, coastal storms, wildfires, drought, and extreme temperatures.

2. Climate Impacts to Transportation Sectors

The transportation sector is characterized by long-lasting and complicated infrastructure systems that can take many years to adapt to stressors and disruptions (Vajjarapu et al. 2020). The transportation sector's climate vulnerabilities can be characterized in several ways. Direct pathways of disruption focus on disruptions to transportation infrastructure itself and has traditionally been the focus on transport system vulnerability research. A list of example impacts can be found in Figure 2, with more detailed explanations of sector-specific impacts in the sections to follow.



	Road	Rail	Waterways and ports
Temperature • Higher mean temperatures; heat waves/droughts; changes in the numbers of warm and cool days • Reduced snow cover and arctic land and sea ice; permafrost degradation and thawing	• Thermal pavement loading and degradation • Asphalt rutting • Thermal damage to bridges • Increased construction and maintenance costs • Reduced integrity of winter roads and shortened operating seasons	• Track buckling • Infrastructure and rolling stock overheating/failure • Slope failures • Signaling problems • Speed restrictions • Asset lifetime reduction • Higher needs for cooling • Shorter maintenance windows	• Damage to infrastructure, equipment and cargo • Higher energy consumption for cooling • Potential for longer shipping seasons • Occupational health and safety issues during extreme temperatures
Precipitation • Changes in the mean values; changes in intensity, type and/or frequency of extremes	• Inundation, damage and wash-outs of roads and bridges • Increased landslides • Bridges scour	• Flooding, damage and wash-outs of bridges • Problems with drainage systems and tunnels • Delays	• Infrastructure inundation • Navigation restrictions in inland waterways due to river water levels changes
Sea levels/storm surges • Mean sea level rise • Increased extreme sea levels	• Erosion of coastal roads • Flooding, damage and wash-outs of roads and bridges	• Bridge scour, catenary damage at coastal assets • Disruption of coastal train operation	• Asset inundation • Navigation channel sedimentation • Maintenance costs

Figure 2. Some examples of climate change impacts on transportation infrastructure and operations.

Along with direct impacts listed above, Markolf et al. (2019) identified the need to understand indirect disruption to capture the complexities revealed within transportation systems and other critical infrastructure systems like energy, water, fuel, communications, and communities. Transportation systems do not exist in isolation and an understanding of these strong interconnections is important to eventually identifying adaptive actions. For example, if a roadway or railway into a port experiences flooding, then the movement of goods, services, and employees is impacted. The port's functional resilience is decreased no matter the status of its infrastructure. Keeping these indirect disruptions in mind, the following sections identify some climate change-related impacts felt by different transportation sectors.

(a) Road

In terms of road transport, structural failures are anticipated in polar regions due to permafrost thaw and increased erosion related to ocean warming, storm surge flooding and loss of sea ice (From IPCC – Melvin et al. 2017; Fang et al. 2018; IPCC Cross Chapter Paper 6). Climate flooding would double the number of delays and lost trips in the Boston metropolitan area by 2100 (Suarez et al. 2005). Median cost of not adapting to climate change impacts on paved roadways in Ghana would be $473.72M by 2100 (Twerefou et. al 2014). Climate change could impact between $1.3B and $4.9B of primary roadways in Mexico (Espinet et al. 2016). US DOT Climate Action Plan lists notable potential impacts to road systems:

- More frequent and severe flooding of underground tunnels and low-lying infrastructure requiring draining and pumping,
- Increased thermal expansion of paved surfaces, potentially causing degradation and reduced service life, due to high temperatures and increased duration of heat waves,

- Higher maintenance and construction costs for roads and bridges due to increased temperatures and exposure,

  Asphalt degradation and shorter replacement cycles, leading to limited access, congestion, and higher costs due to higher temperatures,

- Culvert and drainage infrastructure damage due to precipitation intensity or snowmelt timing,
- Increased risk of vehicle crashes in severe weather.

(b) Rail

Railways are a global asset, with estimates of conventional railways totaling around 1,060,000 line kilometers in 2018 (IEA 2023). Many of these railways and supporting infrastructure were constructed more than 150 years ago - far exceeding design lifetimes - and their performance during weather extremes is uncertain (Palin et al. 2021). In terms of rail transport, heat-related delays and infrastructure damage could cost the United States up to $60B by 2100 (Chinowsky et al. 2019). Further, impacts from sea-level rise, storm surge, and coastal flooding threaten further economic losses and disruption (Neumann et al. 2021). These disruptions will have cascading impacts across global supply chain and freight transportation networks as well as disruptions to commuter mobility and community accessibility. To summarize these impacts, Palin et al. (2021) have identified the following:

- System downtime, derailments, slower travel times due to rail buckling and thermal expansion on extremely hot days,
- Damages to overhead lines, rock falls, and icing and breakage due to low temperatures and freeze-thaw action,
- Slope failures, flooding, electronic equipment damage, and bridge scour due to flooding and landslides,
- Infrastructure slope failure, track misalignment, and pole misalignment due to drought and soil shrinkage/drying,
- Scour and structural damage due to coastal flooding and waves.

Considering road and rail transport together, in the East Coast of the United States, for example, 3800 km of roadways and railways are at risk for temporary or permanent inundation should sea levels increase by 58cm (Wright and Hogan 2008). In Europe, ten-fold increases in damages associated with buckled pavements due to heat stress, coastal and inland flooding, windstorms, and forest fires are possible (Forzieri et al. 2018). A further compounding reality is that many road and rail infrastructure networks already exhibit significant deterioration and have been built (Neumann et al. 2021).

(c) Ports and Inland Waterways (IWW)

Ports and Inland Waterways (IWW) are severely vulnerable to numerous climate stressors and disruptions because of its geographic location in low-lying areas adjacent to coasts and river plains, its highly streamlined, optimized, and unique regional operations, and the far-reaching and occasionally compounding supply chain impacts of any delays or accidents (PIANC 2020A). For example, Christodoulou and Demirel (2018) found that up to 60 per cent of the European Union seaports may be under high risk for inundation by 2100 under maximum SLR (1 meter). Ports and IWW are critical to global trade, moving over 11 billion tons of goods (or 80% of global trade) and they are particularly critical for developing countries, who account for 61% of the total global maritime trade (UNCTAD 2022). Right now, if no adaptation measures are taken, estimates of global cost to shipping due to sea level rise and stronger storms could total an additional US$25 billion every year by 2100 (more than recent total annual operating profits; Van Houtven et al. 2022). The World Association of Waterborne Transportation Infrastructure (PIANC) Navigating a Changing Climate initiative describes a variety of climate impacts from the navigation zone to the processing and manufacturing plants to the hinterlands where products are bound (PIANC 2020B). These impacts include:

- Suspension of port operations and damage to infrastructure due to to overwhelmed draining systems or high groundwater,
- Terminal inundation or levee overtopping due to high river flow levels or storm surge,
- Impacts to navigation due to high river flow velocities or sea state changes (agitation, extreme waves)
- Channel closures or draft restrictions due to low river flow velocities or drought,
- Draft restrictions or increased dredging costs due to sediment or debris transport, accumulation, and erosion,
- Reduction or restrictions to port operations due to low visibility (fog, snow or other precipitation),
- Infrastructure degradation or corrosion above design expectations due to changes in water chemistry,
- Impacts to navigation and port operations due to changes in wind speed, strength, direction, or duration,
- Damage from exposure of employees, infrastructure, and goods due to extreme heat, humidity or cold,
- Additional requirements or legislation due to changes in ecology - vegetation growth, species migration, invasive species.

(d) Airports

Air travel is vulnerable to even short weather events, causing significant and widespread cancellations or delays (Ryley et. al 2020). The projected climate impacts most likely to affect aviation directly are issues related to changes in precipitation and temperature, wind, extreme weather, and sea level rise (Burbidge 2018). Presently, many airports are only 10-20 feet above mean sea level with a few below sea mean sea level (Schiphol Airport, Amsterdam; Louis Armstrong Airport, New Orleans; Budd and Ryley 2012). That number could increase greatly depending on the rate of sea level rise. By 2100, one study estimates 100 airports are projected to be below mean sea level under 2°C of warming with a large number of airports at risk in Europe, Northern America and Oceania, but with the highest risks in Southeast and East Asia (Yesudian and Dawson 2021). This same study identified a common concern for many transportation systems: adaptation financing will likely not be equitably available to small coastal airports. This could result in devastating consequences for low lying islands that rely on air travel as an economic, social, and medical lifeline (Yesudian and Dawson 2021). The conversation about climate change has primarily been focused on mitigation, but adaptation is an emerging concern (Ryley et al. 2020). In 2018, 86% of the European Organization for the Safety of Air Navigation’s survey respondents indicated that climate change would be essential for the industry (Burbidge 2018). Several additional impacts identified by the USDOT (2022) and others include:

- Air traffic disruption due to severe weather and precipitation events that impact arrival and departure rates or require flight cancellations, sometimes for extended periods of time,
- Limits to aircraft performance (i.e. payload or range) due to increased temperatures,
- Challenges to airplane takeoff and landing due to shifting wind direction, wind strength, and increasing temperatures,
- Turbulence and travel time changes due to changing wind patterns,
- Reductions to airport capacity and network disruption due to rising sea levels.

C. Use of stress test as a step to determine if an intervention program is needed to ensure transport infrastructure provides an adequate level of service in the context of climate change hazard

To manage infrastructure in a way to cost-efficiently minimise the potential consequences of extreme events on the service provided, it is necessary for transport infrastructure managers to:

(a) have a clear idea of the set of services that the infrastructure is providing and an understanding of its resilience against potentially disruptive natural hazard events, and,

(b) to understand how the resilience of a transportation network can be modified to counteract the loss of service following a hazard event and to provide specified levels of service during and following the occurrence of extreme events – that is, to set resilience targets.

This framework contains the steps to measure the resilience of transport systems with respect to a defined service or set of services and set targets of resilience, using stress tests. The steps will help ensure that resilience deficiencies and their causes are correctly identified and that the most cost-efficient action can be taken to improve the resilience to an adequate level.

The steps are to be done in an iterative fashion from a high general level to a low detailed level if needed. The iterations are to be done keeping in mind that for more detailed quantitative evaluations, more time and eventually computer support will be required. At each iteration, stress tests are done.

A single stress test is a scenario where at least one part of the entire system as defined is considered to be worse than expected. For example, if the scenario is to represent how a regional transport system is to work in the upcoming calendar year, one could imagine the scenario as normal or one could imagine the scenario assuming that one of the following occurs, e.g.:

(a) the 1/500-year rain fall occurs,

(b) the scour depths due to the worse flood expected are worse than expected,

(c) the foundations of the bridges are shallower than expected and therefore the damage due to the expected heavy rainfall event are higher than expected,

(d) the flood protection mechanisms with respect to the expected flood waters are far less effective than expected,

(e) the number of work crews available to restore transport infrastructure following the expected damage are lower than expected, or

(f) the need for transport on the infrastructure during or after the event are higher than expected.

Stress test are to be done with the variables having values representing higher percentiles, e.g., 95th percentile, of their assumed distributions than mean or median values.

The level of resilience considered acceptable varies from situation to situation. It depends on:

- norms on individual and societal risk, where individual risk indicates the distribution of the risk over the potentially affected individuals, and societal risk describes the relationship between frequency and the number of people suffering from a specified level of harm,
- whether there are possibilities to increase the resilience and how costly these are, which is similar to the economically optimal level of risk.

Stress tests should be done first at a relatively high level of abstraction, and then repeatedly, at increasingly lower levels of abstraction until it is decided that the level of risk is either acceptable or not, each time determining the level of performance in specific situation. The lower the level of abstraction the greater the time and effort required and the greater the sophistication of the models used.

Once the results of the stress tests are generated and evaluated, it can be decided if the system passes or fails the stress tests. If the resilience level is acceptable, no interventions are required. If the resilience level is not acceptable, resilience enhancing interventions are required. If the resilience level is not acceptable, an intervention program needs to be constructed that will optimally increase the resilience to an acceptable level.

The interventions included in the intervention program may be on any part of the system, e.g.:

- diverting a river so it does not come in contact with infrastructure during a flood,
- the strengthening of infrastructure so that it can resist the flood waters during a flood, and
- the construction of a second road so that there is little disruption to traffic flow if the first road is washed out from flood waters.

The planned interventions cannot require the use of more resources than are available, and should achieve the maximum resilience possible for the available resources.

D. Stress test steps

1. General

The steps to conduct a stress test that are presented in this section have been constructed keeping in mind that different decision situations will require different types of models that will provide different levels of detail. In addition, in many cases it is desirable to conduct stress tests iteratively. This is consistent with the principles of:

- working in phases, e.g., qualitative analysis over a short period of time first, and quantitative analysis over a longer period later if required,
- working from a higher level of abstraction to a lower level of abstraction, e.g., first analysis delivers less detailed information, and later analysis delivers more detailed information, and
- thinking in possibilities, e.g., there are many possible stress tests to conduct and many ways to perform stress tests once they are set.

2. Define stress test

The *define stress test* step is to determine what needs to be checked to be able to say that there are acceptable levels of infrastructure related resilience due to natural hazards or that resilience enhancing interventions need to be planned and executed. This includes the definition of the acceptable levels of reductions in service and increases in intervention costs, e.g., there is an acceptable level of infrastructure related resilience with respect to flooding if a 100-year flood event does not cause losses in infrastructure restoration costs and lost travel time in excess of 1 per cent of GDP.

This step includes the generation of preliminary thoughts on the area to investigate and the period to be considered. It will affect the definition of the system representation, and the requirements to conduct the stress test, in terms of both input, e.g., man-power, and output, e.g., the accuracy of the results or the number and types of scenarios to be investigated. It will also affect the scope and the level of detail of the assessment. Thought needs to be given to the levels at which the stress test needs to be conducted. For example, is it important that the resilience to both floods and heavy rainfall is above a threshold value, or is it important to have the resilience to floods above one threshold value, and the resilience due to heavy rainfall above another threshold value, or both.

The definition of the stress test is difficult in that it requires multiple stakeholders bringing together their opinions and feelings into multiple coherent questions to be answered. The stakeholders to be involved depend on the specific situation, but are likely to be the infrastructure managers, politicians, the environmental protection agency, regional development representatives, and technical experts focused on hazard aspects, e.g., flood modelling, infrastructure aspects, e.g., structural engineers, and consequences aspects, e.g., traffic modelling experts, and construction aspects, e.g., experts on reconstruction efforts. An example question could be concerning the extent of traffic disruption expected following the occurrence of a 1/100-year flood, where an acceptable limit may be placed on the total amount of additional travel time and on the time with which the infrastructure is to be restored.

This step results in a set of clear questions which, once answered through the stress test, will either tell you that the current levels of infrastructure resilience to natural hazards are acceptable or, alternatively, that resilience enhancing interventions need to be planned and executed.

3. Determine your approach

The *determine approach* step involves determining:

(a) which type of approach, e.g., qualitative, semi-quantitative or a quantitative approach will be used, in which form, and at what point in the process, (in general qualitative approaches take less time, are more approximate and are more holistic, and quantitative approaches take more time, are more exact and are used to investigate specific sets of scenarios; additionally, qualitative approaches should be used first in the analysis of resilience, and if the results of the qualitative approaches are not satisfactory, then the more in-depth quantitative analyses can be done on the parts of the system where more precision is required). The increase in the level of detail from moving from a qualitative analysis to increasing quantitative analyses can also be done in an iterative way, e.g., by first employing 1D hydraulic models to predict the extent of flooding, and then proceeding to 2D or 3D models, if needed, and if feasible, considering the available resources.

(b) whether or not computer support will be used, and if yes, which form and at what point in the process. In general, for the more quantitative approach the more computer support is required. The exact computer support required will, of course depend on the parts of the system to be investigated and the detail expected. For example, if one is to use computer support to investigate the possibility of bridges being overtopped in a flood situation, the computer models will have to be able to simulate three-dimensional water flow, and

(c) the level of involvement of representatives from different stakeholder groups, in which form and at what point in the process. For example, a qualitative approach may be done by having an analysis team prepare the different parts of the analysis and then in a workshop with the presence of all relevant stakeholders, present and discuss the analysis and the results. After obtaining feedback from the stakeholders, the analysis team could revise the analysis if necessary. The number and frequency of the workshops will of course depend on the duration of the project and wishes of the stakeholders. A nine-month qualitative analysis might have 5-7 to workshops each 4 hours in duration.

The *determine approach* step also involves making decisions about how the resilience to multiple hazards are to be considered. For example, if one is considering heavy rainfall and thresholds for acceptance is to be placed on the individual stress test used or on some form of aggregated results. More specifically, should a threshold for acceptance be placed on the amount of travel time caused by, for example, a 1/100 year 24hr rainfall and a 1/100 year earthquake separately, or should there be a threshold on a cumulative value?

4. Determine your transport system representation (infrastructure, environment, and organisation)

The *define system representation* step involves:

(a) defining the boundaries of the system both spatially and temporally,

(b) defining the events to be included,

(c) defining the relationships between the events, and

(d) the scenarios to be considered.

Remembering the principle to work from a high level of abstraction to a low level of abstraction, the type and number of events considered vary depending on the level of detail required in the analyses/model. This means, for example, that the infrastructure events to be included in a first iteration of the process might be defined through modelling a 10 km road link as 3 bridges, 4 road sections and a tunnel, which can each either be working or not working.

In the second iteration of the process the infrastructure events to be included might be defined through modelling the 10 km road link as in the first iteration, except subdividing each of the bridges into elements, such as columns, bearings, decks and abutments. The define system representation step will likely require numerous iterations the first time it is done. If a stress test is done more than once on the same system, e.g. at five year intervals, there will be a reduction in iterations.

The substeps required are: (i) define boundaries, (ii) define events, (iii) define scenarios, (iv) define relationships and (v) determine models. They are explained in the subsequent sections.

(a) Define boundaries

The *define boundaries* step involves defining the system that is going to be analysed/modelled, both spatially and temporally.

(i) Definition of the considered system

This system includes all things required to determine if there are acceptable levels of resilience due to natural hazards, including

- the natural environment, e.g., amount of rain, amount of water in rivers,
- the physical infrastructure, e.g., the behaviour of a bridge when subjected to high water levels, and
- human behaviour, e.g., traffic patterns when a road bridge is no longer functioning, how restorations interventions are prioritized.

As it is necessary to consider the system over time, it is also necessary to consider the spatial and temporal correlation between events and activities within the investigated time period. This includes the consideration of assumptions, agreements as to how the system will react in specific situations, and the consideration of cascading events. It should be kept in mind that conducting stress tests requires taking into consideration realisations of all relevant stochastic processes within the investigated period.

This in turn requires that models be built that are sufficiently good representations of the hazards, infrastructure, and consequences, as well as the interactions between them so that there is an appropriate understanding of the system and that the risks and the effectiveness of the intervention programs can be determined. For example, heavy rainfall in a region may cause flood waters to damage bridges but also trigger landslides that may come in contact with the roads. Analysts in this case are going to have to model how much rainfall in what period of time can trigger a landslide. One option to model this at a very high abstract level is simply with expert opinion. Another, however, is to construct a model related to the amount of rainfall per unit time, the amount of water currently in the soil, and the amount of evaporation possible, including temperature variations over time. Analysts and stakeholders will have to determine the level of detail that they consider sufficient.

(ii) The spatial boundaries

The definition of spatial boundaries defines the part of the natural and man-made environment to be specifically analysed/modeled, as well as how it is to be subdivided. This includes the definition of where the assets are located, where the source and hazard events can occur, and where the consequences could take place.

The spatial boundaries are different depending on the part of the system being analysed. For example, the infrastructure to be considered might be that inside the physical boundaries of a city, but the rainfall to be considered might be that of a catchment area that is much larger than the physical boundaries of the city. It is usually easy to specify the possible locations of the events, hazards and objects that are of direct concern. It is more difficult, however, to specify the locations of the events, hazards, and objects that might be included in the scenarios to be analysed in a stress test. This is more difficult because it is required to think through scenarios, in which there are events that you might not have yet identified. For example, if one considers the flooding of a region, which might happen because of a dam failure far up the river, in a region outside your originally defined area.

This becomes even more difficult when the location of possible consequences is to be specified. Consequences can be far away from the location of the events, hazards, and infrastructure, and may be outside the direct area of responsibility of the infrastructure manager, e.g., the collapse of a highway bridge on a trans-European highway network can have consequences on the free flow of goods in many countries.

(iii) *The temporal boundaries*

As with the spatial boundaries, the temporal boundaries are different depending on the part of the system being analysed. The definition of the temporal boundaries defines the period over which the natural and man-made environment to be specifically analysed/modelled, as well as how this period is to be sub-divided. For example, the rainfall event considered to occur in the upcoming year may be the 1/100 year rainfall event, but the consequences of this event might be measured over the following two years after its occurrence, or until the system is restored to normal.

Additionally, a system can be analysed/modelled as being static or dynamic. When the system is analysed/modelled as being static, the changes over time are not considered, e.g., the growth in traffic flow. When it is analysed/modelled as being dynamic, they are. The decision on which is used is situation dependent. One important consideration when deciding to model a system as static or dynamic is the time required to do the analysis, as dynamic models take considerably longer than static ones. Another important consideration is how dynamic the system is. For example, if one is to construct a stress test on an urban transport infrastructure once every 10 years and a new highway is to be built in the region during that 10-year period, it would indicate that the system should be modelled dynamically to capture the changes happening in each year of the 10-year period.

This step ends with clear definitions of the spatial and temporal boundaries of each part of the system to be analysed.

(b) Define events

The *define events* step involves identification of all events (cascading and non-cascading) that are to be analysed/modelled. These events are, in general, grouped from source events to societal events. Source events are ones that, at least from a modelling perspective, are considered to simply happen. Societal events are events to which human activity can be associated and, therefore, can be quantified when estimating resilience. All events other than the societal events are only precursors to societal events and are only considered in the estimation of resilience by how they effect human activity, e.g., repairing a bridge, or not being able to travel.

Although the number of event types considered can vary depending on the specific type of problem and the desired level of detail in the analysis/model, the five basic types of events considered are source events, hazard events, infrastructure events, network use events, and societal events. All events are described in space and time, and measures of the intensities of interest should be given. The areas range from small, e.g., a tunnel collapse, to large, e.g., to traffic patterns being interrupted across Europe. The time periods range from a few minutes, e.g., avalanches, to over a few days, e.g., flood, to several months, e.g., heat waves. Measures of the intensities of the events should represent the values of event attributes that are of interest. The number of intensity measures used to describe the events depends on the problem investigated and the level of detail required in the analysis. Details are given in Table 1.

The necessary detail to be used depends on the specific problem and the level of detail desired. If events at any level, or complete ranges of the values of intensity measures are excluded, it should be explicitly explained and documented why, because in the following risk estimation, the risk coming from those events will be excluded.

This step ends with the generation of a list of all events to be included in the system representation.

Table 1
Basic event types

Event type	*Description*	*Examples*	*Comments*	*Example intensity measures*
Source	An event that may lead to a hazard event.	Rainfall, Snow	It is the first event in a scenario that will lead to a societal event. A source event may also be referred to as an initiating event.	For a rainfall source event, rainfall of pattern *x* with water per minute of over y mm^2/s for more than 5 hours.
Hazard	An event that may lead to an infrastructure event. A hazard event may also be referred to as a load event.	Flood, Landslide, Snow avalanches	A hazard event is normally considered to have a source event, but is sometimes modelled directly as a source event itself. In addition to leading to an infrastructure event, a hazard event may also lead to another hazard event, e.g. earthquake triggers landslide.	For a flood hazard event, water levels reaching x m depth in locations a, b and c, and amounts of water per second coming in contact with bridge *i* over $j\ m^3/s$.
Infra-structure	An event that is a change in the infrastructure that may lead to a change in infrastructure use or a change in human behaviour	The state of all infrastructure objects being considered at each instance of time during a flood	In the determination of the infrastructure events thought must be given to which infrastructure object is affected by which hazard and the likely condition states that the object may have if subjected to a hazard. This is a difficult task as in many cases many objects could be affected but the effect might range from very small, e.g. yielding of a reinforcement bar in a bridge during an earthquake, to very large, e.g. collapse of the bridge.	For a bridge collapse, damage resulting in full closure of the road, damage results in the closure of one lane of traffic, damage resulting in no closure of the road.
Network use	An event that is a change in how the infrastructure is used that may lead to a change in human behaviour	The state of use of the network following closure of part of the network due to the flood	The probabilities of these events occurring are particularly difficult to estimate as their occurrence depends on spatial and temporal correlation, and physical relationships between	For example, due the freight corridor between Rotterdam and Genoa being closed 50% of goods is put onto trucks, 40% of goods is diverted over other

Event type	*Description*	*Examples*	*Comments*	*Example intensity measures*
			initiating events, hazards and infrastructure events. The latter, can lead to cascading events.	train routes and 10% is not delivered.
Societal	An event that is a change in human behaviour	The actions of persons or groups of persons to which a value can be placed including the restoration activities following a flood and the lost travel time incurred by the users of the network.	In order to model the actions of persons or groups of persons, it is often beneficial to group them into categories based on their general behavior, which in turn is coupled with how their behavior is to be modelled. Societal events may lead to other societal events. If they, however, do not, then a value needs to be assigned to the event. This value then enters the risk assessment as a consequence.	Amounts an infrastructure manager spends on reconstruction amounts users spend in additional travel time

(c) Define scenarios

The *define scenario* step involves linking the events together from the source events to the societal events, in the form of an event tree. A very simple example is given in Figure 1. The very simple example is used for clarity, but it should be clear that the event trees required in most situations will have many more branches and many more sub-categories of the events used in Figure 1. To build the event tree, it is necessary to determine the value of the intensity measures defined in the *define events* step that will provide clarity on how events are considered to be related. The identification of the scenarios should be done in this step without an explicit estimation of their probability of occurrence or putting a value on the consequences.

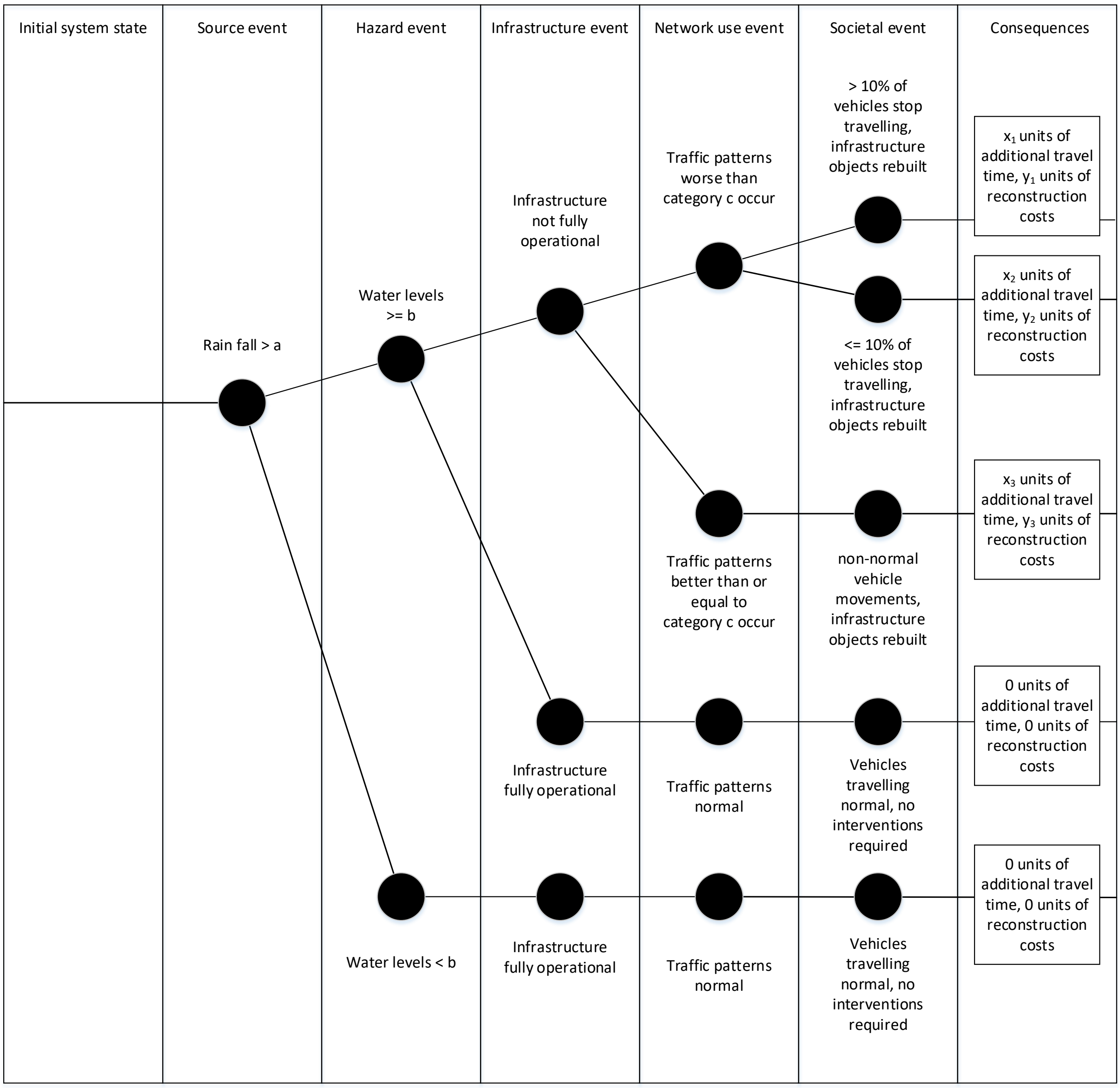


Figure 1. Example of a simple event tree for the definition of scenarios

For each system representation there are an infinite number of scenarios and an infinite number of ways to represent these scenarios, i.e., an infinite number of ways to represent reality and how it will unfold over time. Particular care needs to be used in the selection of the appropriate scenarios to analyse, as the set of scenarios should cover everything important to the stakeholders. It is important to avoid arriving at the end of the stress testing process and having a stakeholder point out that they are not happy with the fact that no stress tests were done, for example considering earthquakes.

In order to generate a sufficient set of scenarios to be included in the stress test, it is useful to consider the following three possible starting points for your scenario generation:

- start with the source events and think forwards through how the infrastructure will be affected and then how humans will react to this,
- start with the societal events and think backwards through how the infrastructure would have to behave to cause such events, and
- start with infrastructure events and think in both directions.

Comprehensive identification of relevant scenarios is important because scenarios excluded in this step will not be included in further analysis and may result in an incorrect estimation of risk. To minimise the possibility of this happening it is important that experts in each area are involved.

This step ends with a list of all scenarios to be analysed.

(d) Define relationships

To estimate the likelihood of the cascading events in the stress test scenarios, models of the relationships between the events are to be developed. For example, to determine the amount of water coming in contact with a bridge during a flood, it is necessary to model how the source of the water (rain), turns into surface runoff, and reaches the river. This model may take into consideration the amount of water that seeps into the ground, evaporates, or is held in temporary retention ponds. The amount of effort to be spent on this depends on the exact problem and the level of detail desired. For example, in some cases it may be sufficient to use fragility curves based on expert opinion to estimate the amount of damage that a single bridge might incur during a flood event.

In other cases, it may be desirable to use component-based fragility curves to estimate the amount of damage a large levee might incur during a flood event given the large number of components that may fail. In general, extra effort should be spent to achieve more detail when it is suspected that the results will add additional clarity for decision-making. If additional clarity is not provided, the extra effort is not worth it.

Although specific examples are given here, the general thoughts apply to all events, i.e., source events, hazard events, infrastructure events, network events and societal events. If possible, the availability of data for modelling relationships should be considered in determining the level of detail to be used. This step may involve investigating parts of the system in depth to ensure that the relationships between events are defined at the desired level of accuracy, e.g., data can be collected on rainfall patterns, water levels in rivers can be collected during rainfall events, bridge columns can be tested to see how they react to water pressures, roads can be closed to observe traffic patterns that might be associated with road closures, and tests can be done to see how long it takes to restore failed infrastructure.

This step ends with clear explanations of the relationships between all events.

(e) Determine models

Once the boundaries, events, scenarios and relationships to be analysed are determined, the specific models to be used to estimate the resilience are determined. These models can range from approximations using expert opinion, e.g., the 1/100 year rainfall will cause the overtopping of the bridge, to simple deterministic relationships, e.g. 1mm of rainfall in the catchment area increase the water height under the bridge by 0.5mm, to advanced simulation models, e.g. a 3D hydraulic model of the catchment area.

The determination of models includes the selection of the software such as Python, R, and Arc GIS, and an estimation of the required hardware and computation power, to be used if computer support is required (Adey et al., 2014, Hackl et al., 2015). This step ends with the selection of all models and software required to estimate resilience.

5. Estimate resilience

In the *estimate resilience* step the probability of occurrence of each of the scenarios and the values to be attributed to the societal events associated with each scenario if it occurs are to be estimated and, when desired, aggregated. For example, the amount of travel time incurred due to the 1/100 flood event and the 1/500 year flood, if these are used as stress tests, will need to be estimated and perhaps aggregated using the probability of occurrence of each in the upcoming year. If multiple measures of service are to be used, e.g., travel time and accidents, then both will need to be estimated for the 1/100 and the 1/500 year flood and aggregated. Additionally, values on a unit of travel time and on accidents will have to be determined if it is desired to combine the values into one single estimate of resilience. The most straight forward way to value service is through the estimation of their monetary values, e.g. a unit of time lost has a value of 20€ and a light injury incurred in an accident has a value of 100’000 €. These values are often available in the existing codes of the countries in which the analyses are being done.

This step can be done with or without computer support, i.e. using a quantitative or qualitative approach, which, of course, can also be with varying degrees of detail, depending on the specific problem, the information, data and resources available. With computer support, the simulations of the reduction in measures of service such as travel time if the 1/100 year rainfall occurred, can be made, e.g. 1’000’000 hours, and then multiplied by the unit value of 20€/hour. Without computer support, experts would be asked what they believe the reduction in service would be if the 1/100 year rainfall occurred, and then multiplied by the unit value of 20€/hour. Methods such as Delphi can be used to synthesize the opinion of experts.

Special attention is required to the certainty with which both the probabilities of occurrence and consequences of each of the scenarios can be estimated. It is advised to investigate the sensitivity of these values to the modelling assumptions and to consider this in interpreting/evaluating the results. Indicators of the sensitivity of these values are:

- the divergence of opinion among experts,
- the availability of information,
- the quality of information,
- the level of knowledge of the persons conducting the risk analysis, and
- the limitation of the models used.

The parameters varied in the sensitivity analysis should be the ones thought to have the most dramatic effect on the resilience values.

This step ends with the estimation of the transport system resilience for the stress test.

6. Estimate resilience

In the *evaluate resilience* step, the meaning of the estimated resilience to stakeholders is verified. This is true regardless of the type of approach, i.e., qualitative, semi-quantitative or a quantitative approach, used.

A large part of this evaluation is the consideration of how stakeholders perceive risks and the consideration of this over- or under-valuation with respect to the analyst’s point of view used in the *estimate resilience* step. Another part, however, is stepping back from the analysis and reconsidering if everything important was modelled in a sufficient way. As systems are never modelled perfectly, it is reasonable that this step may lead to a decision maker deciding something different than the stress test might indicate. The deviation should, however, be explained.

In this step, decisions are made as to whether or not the stress test has been satisfactorily done, including consideration of the appropriateness of the definition of the stress test, the approach used, the system representation used and the estimation of the resilience itself. This step ends with one of the following decisions being made:

(a) The stress test was conducted satisfactorily and resilience levels acceptable (Stress test passed)

(b) The stress test was conducted satisfactorily and resilience levels not acceptable (Stress test failed)

(c) The stress test was not conducted satisfactorily (Stress test provisionally passed or failed and more analysis is required)

When the stress test is judged not to have been conducted satisfactorily, it means that it has not been done to a level of detail, or in a way, where you can say whether or not the resilience levels are acceptable or not. This might happen because the system, or parts of the system, were not modelled in sufficient detail, or because there is too much uncertainty associated with the models used.

If the stress test is not done satisfactorily, the parts of the system to be analysed in more detail will have to be determined. If the stress test is either passed or failed then the intervention program, i.e., determining the resilience enhancing interventions to be executed in the near future, can be developed. If the stress test is passed, there will be no resilience enhancing interventions to be conducted.

7. Determine parts of system to be analysed in more detail

In this step, the parts of the system that must be analysed in more detail in the next iteration, if any, are determined. The parts that are likely to generate the most reduction in uncertainty, in the resilience estimation are selected. Care must be given here to not only select parts of the system where it is assumed that a reduction of uncertainty will increase resilience so that the stress test can be passed, i.e. the reduction of uncertainties that may decrease resilience should not be neglected. To avoid preferential selection of system parts, the uncertainties related to each part of the system need to be determined. In many cases, this will be done using expert opinion. For example, there is high uncertainty in the expected rainfall and in the traffic patterns that might emerge following the collapse of a bridge, but there is low uncertainty in how the bridge will behave if in contact with water of x m^3/s and in how long it will take to reconstruct the bridge following failure.

A list of ways to reduce this uncertainty, along with their likely benefits and costs, should be generated. This list of possibilities should include conducting in depth investigations on parts of the system, e.g., load testing bridges and running more detailed flood simulation models. The parts of the system to be analysed in more detail can then be determined taking into consideration the available resources, including both effort and time frame. If there are resource constraints, the parts of the system to be analysed in more detail should be the ones that will yield the largest reduction of uncertainty for the available resources.

E. Case studies

This section is contingent on projects to apply the stress test framework.

F. Additional recommendations

This section can provide recommendations/lessons learned from the case studies. It is also contingent on projects to apply the stress test framework.

G. References

Budd, L.C.S., and T.J. Ryley. 2012. Chapter 3. An international dimension: Aviation. In Ryley, TJ., and Chapman L. eds. Transport and Climate Change. Emerald, Bingley, UK.

Burbidge, R. (2018). Adapting aviation to a changing climate: Key priorities for action. Journal of Air Transport Management, 71, 167-174.

Chinowsky, P., J. Helmen, S. Gulati, J. Neumann, J. Martinich. 2019. Impacts of climate change on operation of the US rail network. Transport Pol., 75, 183–191, doi: 10.1016/j.tranpol.2017.05.007

Espinet, X., A. Schweikert, N. van den Heever, P. Chinowsky. 2016. Planning resilient roads for the future environment and climate change: quantifying the vulnerability of the primary transport infrastructure system in Mexico. Transport Pol., 50 (2016), pp. 78-86, 10.1016/j.tranpol.2016.06.003

Fang, Z., P.T. Freeman, C.B. Field and K.J. Mach, 2018. Reduced sea ice protection period increases storm exposure in Kivalina, Alaska. Arct. Sci., 4(4), 525–537, doi:10.1139/as-2017-0024.

Forzieri, G., A. Bianchi, F. Silva, M. Herrera, A. Leblois, C. Lavalle, J. Aerts, L. Feyen. 2018. Escalating impacts of climate extremes on critical infrastructures in Europe. Global Environmental Change, 48, 97–107, doi: 10.1016/j.gloenvcha.2017.11.007

Gratton, G., Williams, P., Padhra, A., and S. Rapsomanikis. 2022. Reviewing the impacts of climate change on air transport operations. The Aeronautical Journal. 126(1295): 209-221. doi:10.1017/aer.2021.109

IEA (International Energy Agency). Global line kilometers of conventional rail, 2000-2018, IEA, Paris. Accessed Jan 22, 2023. https://www.iea.org/data-and-statistics/charts/global-line-kilometers-of-conventional-rail-2000-2018, IEA. Licence: CC BY 4.0

IPCC AR6 (International Panel on Climate Change Sixth Assessment Report) 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability.

Melvin, A.M., et al., 2017. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. Proc. Natl. Acad. Sci., 114(2), E122–E131, doi:10.1073/pnas.1611056113.

Monioudi, I.N., et al., 2018. Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): The case of Jamaica and Saint Lucia. Reg Environ Change, 18(8), 22112225, doi:10.1007/s10113-018-1360-4.

Neumann, J.E., Chinowsky, P., Helman, J. et al. Climate effects on US infrastructure: the economics of adaptation for rail, roads, and coastal development. Climatic Change 167, 44 (2021). https://doi.org/10.1007/s10584-021-03179-w

Palin, E.J., Stipanovic Oslakovic, I., Gavin, K. and Quinn, A., 2021. Implications of climate change for railway infrastructure. Wiley Interdisciplinary Reviews: Climate Change, 12(5), p.e728.

PIANC (World Association for Waterborne Transport Infrastructure). 2020A. Resilience of the Maritime and Inland Waterborne Transport System. PIANC Report Number 193. https://www.pianc.org

PIANC (World Association for Waterborne Transport Infrastructure). 2020B. Climate Change Adaptation Planning for Ports and Inland Waterways. PIANC Report Number 178. https://www.pianc.org

Ryley, T, Baumeister, S and Coulter, L. 2020. Climate change influences on aviation: A literature review. Transport Policy, 92. pp. 55-64. ISSN 0967-070X orcid.org/0000-0002-8072-2534

Schweikert, A, Chinowsky, P., Kwiatkowski, K., and X. Espinet. 2014. The infrastructure planning support system: analyzing the impact of climate change on road infrastructure and development. Transport Pol., 35 (2014), pp. 146-153, 10.1016/j.tranpol.2014.05.019

Spirre Clark, S., Cheseter, M.V., and T.P. Seager. 2018. The vulnerability of interdependent urban infrastructure systems to climate change: could Phoenix experience a Katrina of extreme heat? Sustainable and Resilient Infrastructure 10.1080/23789689.2018.1448668

Storlazzi, C.D., et al., 2018. Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. Sci. Adv., 4(4), eaap9741, doi:10.1126/sciadv.aap9741.

Suarez, P., W. Anderson, V. Mahal, T.R. Lakshmann. 2005. Impacts of flooding and climate change on urban transportation: a systemwide performance assessment of the Boston Metro Area. Transport. Res. Part D, 10 (2005), pp. 231-244, 10.1016/j.trd.2005.04.007

Twerefou, D.K., Adjei-Mantey, K. and Strzepek, N.L., 2014. *The economic impact of climate change on road infrastructure in sub-Saharan Africa countries: evidence from Ghana* (No. 2014/032). WIDER Working Paper.

UNCTAD (United Nations Conference on Trade and Development). 2022. UNCTAD Handbook of Statistics. Available at https://unctadstat.unctad.org/EN/Index.html (accessed 22 January 2023).

USDOT (U.S. Department of Education). 2021. Climate Action Plan - Revitalizing Efforts to Bolster Adaptation and Increase Resilience. Office of the Secretary of Transportation. Washington, DC. https://www.transportation.gov/sites/dot.gov/files/2021-10/Climate_Action_Plan.pdf

USGCRP (U.S. Global Change Research Programs Fourth National Climate Assessment). 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.

Vajjarapu, H., Verma, A., and A. Hemanthini. 2020. Evaluating climate change adaptation policies for urban transportation in India. International Journal of Disaster Risk Reduction, Volume 47. 101528, SSN 2212-4209, https://doi.org/10.1016/j.ijdrr.2020.101528.

Van Houtven, G., Gallaher, M., Woollacott, J., Decker, E., 2022. Act Now or Pay Later: The Costs of Climate Inaction for Ports and Shipping. Environmental Defense Fund and RTI International. https://www.edf.org/sites/default/files/press-releases/RTI-EDF%20Act%20Now%20or%20Pay%20Later%20Climate%20Impact%20Shipping.pdf

WEF (World Economic Forum). 2019. “The Global Risks Report 2019”, 14th Edition, World Economic Forum Geneva, ISBN: 978-1-944835-15-6.

Wright, K.M. C. Hogan. 2008. The Potential Impacts of Global Sea Level Rise on Transportation Infrastructure. ICF International, Washington, D.C. (2008)

Bryan T. Adey1, Jürgen Hackl1, Juan Carlos Lam1, Pieter van Gelder2, Peter Prak3, Noel van Erp2, Magnus Heitzler4, Ionut Iosifescu4, Lorenz Hurni4 Ensuring acceptable levels of infrastructure related risks due to natural hazards with emphasis on conducting stress tests

Full reference for (Adey et al., 2014, Hackl et al., 2015)