Chapter 2. Transport infrastructure: Climate and extreme weather impacts and costs

Individual assets and groups of infrastructure elements are vulnerable to a number of climate and weather-related phenomena. This chapter will review the composition and life cycle of different transport infrastructure asset classes and will describe their exposure and vulnerability to disruption, damage and failure in light of climate-related factors. It will also provide an indicative overview of some of the potential costs faced by the transport sector as climate regimes evolve.

Transportation asset systems

This chapter reviews transport asset systems and highlights the range of climate-related impacts that these can be expected to face under a changing climate regime. It identifies meteorological variables involved in designing different transportation infrastructure. It then discusses five facility types: roads, railroads, airports, sea ports and inland waterways. Impacts for each infrastructure type are described, along with their underlying causal mechanisms. Finally, it presents a range of possible protective actions that could lessen the vulnerability of each infrastructure class to climate change.

Transport networks and the services they provide are indissociably embedded in society. They underpin economic productivity and prosperity and contribute to social well-being. They are fundamental to the delivery of vital services and yet are generally managed in a broadly decentralised manner, especially when considering cross-modal co-ordination. As wealth increases, so too do expectations regarding the availability and quality of transport networks and services. Transport networks are expected to be operational at all times and under a wide range of conditions. Diminished asset availability, condition or outright failure can lead to network disruptions entailing significant economic losses and negative safety outcomes. In many cases these disruptions may be short-lived but with asset failure comes the risk of longer-lasting network interruption and expensive rehabilitation or replacement costs. Numerous actors intervene to operate and maintain asset services that are often taken for granted until they are no longer available. Crucially, transport services depend on a system of systems that at their base depend on individual asset components that are vulnerable to climate change.

In some ways, the potential vulnerability of transport networks to climate change is “built” into infrastructure. Transportation infrastructure is designed and constructed according to engineering standards that incorporate various climate-related factors such as temperature, precipitation, humidity and wind. Assets located in coastal and estuarine zones also incorporate sea-level parameters. The risk under a changing climate regime is that some of these parameters may change beyond the design specifications incorporated into the existing asset base and that are still used for new construction. This may lead to accelerated deterioration or outright failure of critical assets. Further complicating the situation is that there is little certainty as to how global climate change may manifest itself at the regional level in terms of the frequency and strength of specific asset-damaging phenomena. This uncertainty affects the scale of initial investments, the return period (and therefore cost) for refurbishments and the impact of maintenance. Climate change may erode the potential benefits of some vulnerable assets and improve the cost-benefit profile of less vulnerable alternatives.

Embedded assets

Transport networks are embedded within the physical context in which they are built. Design and siting decisions for infrastructure must account for topography, hydrology, geology, pedology and coastal geography. This “base layer” is what determines specific infrastructure design treatments and, in some important ways, the cost of infrastructure construction. On top of this are layered transport and other networks (water, energy, communication) composed of multiple infrastructure objects (bridges, pavements, drainage, geotechnical works, etc.), themselves composed of asset sub-components. Climate change impacts related to these will almost certainly manifest themselves over the mid- to long-term and this will have an incidence on maintenance and repair costs as well as on the costs (or benefits) related to network availability.

These networks, in turn, enable a range of activities such as settlement, manufacturing, agriculture and traffic. At the same time, the extension or upgrading of transport infrastructure can lead to new activity patterns. More fundamentally, transport as a derived demand may be impacted by climate change. Koetse and Rietveld (2009) point out that climate change could impact the availability or desirability of tourist destinations (e.g. by opening up new opportunities or, conversely, rendering existing tourism destinations unpleasant because of heat or storminess) and could lead to new patterns of agricultural production which could shift certain trade flows away from existing pairs. Besides altering patterns and intensities of human activities over the long run, climate change could also erode the economic viability of certain coastal areas (Hallegate et al., 2013). These changes will have an impact on transport demand and could lead to over- or under-supply of transport infrastructure and related opportunity costs.

Asset life cycle: Maintenance requirements and climate exposure

Transportation infrastructure assets require continuous attention in terms of maintenance, to counter deterioration. Indeed, once new infrastructure has been built, it will need to be operated and maintained throughout its useful life in order to deliver expected benefits. Many road and to a certain extent, rail, airport and waterborne transport asset systems may seem "perpetual" in that they are in the "operate and maintain" part of their life cycle with no expectation of closure, decommissioning, deconstruction or demolition (CIRIA, 2009). It is not uncommon for much of the existing infrastructure stock to have been in service for longer than the current design life of equivalent assets as is the case in the United Kingdom (CIRIA, 2009). Funding of operations and maintenance are a direct result of capital spending decisions and may be expected to extend indefinitely into the future for many assets – maintenance expenditures should be therefore taken into account over an indefinite (life cycle of the infrastructure) timeframe for these assets and asset systems. While the expectation may be that transport services are "perpetual", that is not the case for physical assets and asset subcomponents which have limited lifespans and which will need to be refurbished and/or replaced. This means that assets will be differently exposed to climate change. For some asset components, the risk is minimal since their design life is shorter than the period over which changes in climate may manifest themselves – e.g. in the case of road surfaces. For other asset subcomponents, the risk is significant since their design life (or effective period of use in the case of existing assets) extends well within climate timescales (e.g. 50+ years).

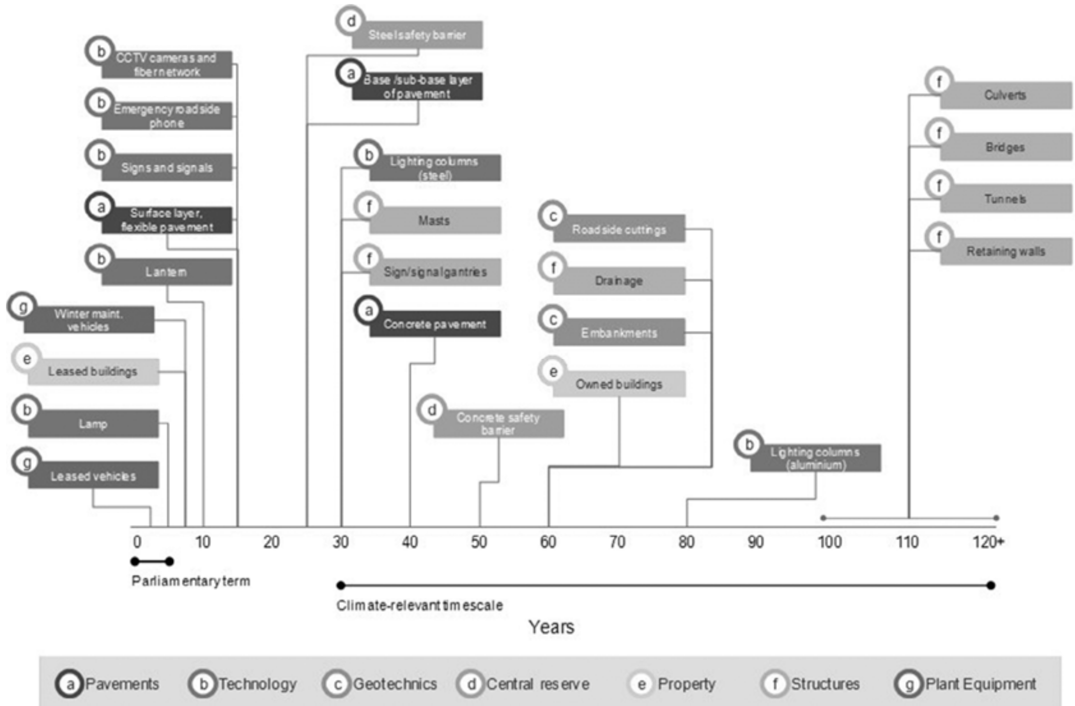
Multiple sub-components

Another point well worth noting is that transport asset systems are in fact a collection of individual, interconnected asset sub-classes that each play a role in delivering expected performance outcomes. For instance, the UK Highways Agency has identified 25 asset components divided into seven asset sub-classes that are critical for the "highway asset" to function properly and meet users' service needs and expectations (Figure 2.1). These asset components all have different lifespans and maintenance/refurbishment schedules that must be adhered to in order to minimise the risk of asset failure and/or service disruption. Assets system components typically outlast political and budgetary cycles and for many longer-life assets, extend into timescales where conditions cannot at this time be accurately predicted (e.g. future demand, climate impacts).

Connected and interdependent systems

Transportation networks are composed of multiple, interconnected infrastructure asset systems. Transport networks also do not operate in isolation to one another nor to other infrastructure networks. They often rely on effective drainage systems and access to continuous power, data and communications services. Robustness and interconnectedness are at the heart of civil engineering and infrastructure design decisions. Engineers must design infrastructure such that it delivers expected services despite being exposed to a wide range stressors, including those linked to weather. They must also design infrastructure systems such that the potential loss of service in one system does not propagate to other systems.

Figure 2.1. **UK Highway Agency Asset System: Component lifespans**



Source: UK Highways Agency, 2011.

Multiple responsibilities

Responsibility for transport infrastructure is not uniform across modes and this will have an impact on the manner in which strategic decisions regarding investment and maintenance are made. The model of ownership and operation will also have an incidence on the choice of risk management and insurance framework adopted. Ports and airports may be owned or operated by the private sector or by public authorities. Rail infrastructure may be owned by one actor and rail services operated by another. Similarly public transport services may be concessioned to private operators or may be the responsibility of local government. Assets owned by the private sector will typically be insured on a market basis while publicly owned assets, and roads in particular, will be self-insured in the sense that damage costs are borne by public authorities.

Local government exposure

Public ownership is generally the norm for road infrastructure but this responsibility is typically split across multiple levels of government. Strategic motorways and major connectors may be under the responsibility of national governments – who may in some cases grant concessions for the operation of these roads to private operators for toll-based operations. These primary roads and motorways carry a significant share of overall traffic. In the UK, the strategic road network represents only 2% of the overall road network length but it carries one-third of all passenger traffic and two-thirds of all freight traffic (DfT, 2013). Nonetheless, despite the disproportionate importance of motorways and major connectors, the overwhelming majority of roads and a significant share of traffic are carried by roads owned and maintained by local and regional authorities. In Australia, for example, the country's 560 local governments own or are responsible for approximately AUS 212 billion worth of assets, in large part comprised of transport and related assets. This responsibility is often not matched with commensurate funding, especially for maintenance. Carter (2013) succinctly notes this tension:

> Local government is asset rich but income poor. The assets include roads, cycle paths, footpaths, water and sewerage networks, levees, dams, stormwater drains…Many of these assets underpin the basic services we take for granted each day. These assets are subliminal in our consciousness until water supply is interrupted, bridges are closed or weight-limited, townships are flooded, or we crash on an unsealed road.

Climate stressors and their impacts on transport infrastructure

Climate "stressors" are those climate variables[1] including temperature (average, extremes and amplitude), humidity, precipitation and wind that either directly or indirectly affect the siting, design, construction, operation or maintenance of transport infrastructure (Meyer et al., 2014). These stressors may be linked to gradual changes in prevailing conditions or may come about suddenly in the context of extreme events.

As noted in Chapter 1, climate change will shift average climate variables as well as the magnitude and severity of natural phenomena. The former includes changes in temperature, precipitation, soil humidity, etc. while the latter include storms, storm surges, flooding (Cochran, 2009). Changes in average values are generally expected to impact infrastructures in the mid and long run, while shifts in the intensity and severity of natural phenomena could already have a direct catastrophic effect on transportation infrastructure today.

Table 2.1. **Climate change stressors: Gradual vs. sudden**

Category	Climate-related stressors
Changes in average values	• Change in average temperature • Change in precipitation • Change in humidity • Sea level rise • Permafrost melting
Changes in the intensity and severity of weather phenomena	• Severe storms • Storm surge • Extreme precipitation • Flooding • Draught • Hurricanes • Heat waves

Source: Compiled from: Larsen et al., 2008; Cochran, 2009; Karl et al. (eds.), 2009; Koetse and Rietveld, 2009; Eichhorst, 2009; Meyer et al, 2011; Inturri and Ignaccolo, 2011; Meyer et al., 2014; Nemry et Demirel, 2012.

For example, increased scouring[2] of bridge abutments could result from a change in longer-term precipitation, runoff and streamflow patterns but this is expected to occur over longer time periods. On the other hand, a severe flood resulting from extreme rainfall or rapid snowmelt could lead a bridge to collapse in a matter of minutes. Such a categorisation is critical for deploying adaptive measures; while catastrophic events require mostly short- and mid-term actions (preparation of emergency response services, infrastructure repair and retrofitting), adaptation to longer-term changes in weather patterns may require design and construction of new transportation infrastructures or re-siting decisions (Cochran, 2009). Typical climate stressors for the two categories are presented in Table 2.1.

What constitutes a climate “stress” is largely tied to the design of infrastructure and the particular intensity of the climate variable. Culverts sized to handle 100 mm of rain in a day may not be affected if 80 mm of rain falls over the course 24 hours. The same culvert may be overly “stressed” and may possibly fail should 80 mm of rain fall in two hours. While specific threshold values for climate stressors are context-specific, there is some value nonetheless in assessing stressor threshold values. Leviäkangas et al. (2012) have estimated rough damage threshold values for extreme weather phenomena (see Table 2.2). These values can serve as guidance for understanding when damaging impacts may emerge during extreme events.

Table 2.2. **Most harmful extreme weather phenomena and their threshold values**

Phenomena	Threshold 1 harmful impacts possible, 0.33	Threshold 2 harmful impacts likely, 0.66	Threshold 3 harmful impacts certain, 0.99
Heat (mean daily temperature)	≥+25°C	≥+32°C	≥+43°C
Cold (mean daily temperature)	<0°C	<-7°C	<-20°C
Rain	≥30 mm/d	≥100 mm/d	≥150 mm/d
Snowfall	≥1 cm/d	≥10 cm/d	≥20 cm/d
Wind (gust speed)	≥17 m/s	≥25 m/s	≥32 m/s

Source: Leviäkangas et al., 2012.

Climate stressors will impact different asset sub-components in different ways. This implies that a transport asset may be affected by a number of climate-related factors, with each factor contributing differently to the degradation of one or more infrastructure elements. This is particularly true for infrastructure comprised of multiple sub-components such as pavements, bridges and tunnels, where changes in weather patterns trigger different deterioration mechanisms.

Climate stressors operate simultaneously or cumulatively thus amplifying their individual impact on infrastructure. For example, the structural integrity of a steel bridge superstructure could be weakened by extreme temperature changes, while higher precipitation will accelerate scouring of its abutments. Ultimately, the bridge may fail due to the cumulative impact of both stressors. In another example, combined hazard-forcing mechanisms, including saturated soils due to increased average precipitation and soil humidity levels, extreme rainfall, and a storm surge, could lead to severe flood damage to roads, bridges and embankments that paralyse transport services. Cumulative climate-impacts don’t have to lead to failure for them to temporarily degrade transport system performance. High winds combined with extreme rains may make a bridge unsafe to use and its approaches temporarily impassable but these impediments will recede after the storm event. Whereas each hazard-forcing mechanism on its own may have resulted in manageable impacts, their combination simultaneously or in rapid succession leads to serious or catastrophic results. Table 2.3 reviews the current understanding of the negative and positive impacts of various climate stressors on transport infrastructure.

Table 2.3. **Overview of climate stressor impacts on transport networks**

Climate stressor	Potential transport infrastructure impacts
Warmer summers	Heat-related deterioration of materials, asphalt rutting, rail buckling. Longer airport runway requirements. Loss of inland navigation capacity due to low water levels. Thermal expansion of bridges and joints. Damage to machinery and engine overheating. Heat damage to ITS systems. Wildfire and smoke risk. Reduced construction and maintenance work hours. Soil subsidence due to drought. Accelerated heave and/or loss of cohesion of permafrost soils.
Warmer winters	Reduced ice and snow removal costs. More opportunities for winter-time maintenance and construction. Potential increase in fogginess. Asset deterioration due to more frequent freeze-thaw cycling. More accessible inland waterways. Loss of use of snow and ice roads; increase in permafrost heave. Increased flood risk due to increase in wet winter precipitation.
Changes in soil and air humidity	Decreased soil humidity can lead to subsidence of geotechnical substrata. Increases in soil humidity can lead increased runoff due to saturation, loss of cohesion resulting in structural instability for bridges, sub-bases, slope cuts and embankments or increased landslide risk. Increases in air humidity, in conjunction with heat, can reduce working hours available for construction, operations and maintenance.
Increased precipitation (average and extremes)	Increase in weather-related crashes, traffic disruptions and delays. Flooding of land transport infrastructure, hydraulic damage to bridge abutments and footings, prolonged standing water damage to geotechnical substrata, culvert failures and road, rail washouts. Collapse of embankments, mudslides, landslides and slope failures. Flooding of subways and public transport facilities (e.g. bus depots). Inability for transport workers to get to their work, increased incidence of slushflow avalanches.
Stronger and more frequent extreme winds	Damage to technical superstructure of roads, railroads, port and airports. Damage to lighting, power and communications networks. Traffic disruption and closures due to felled trees. Temporary closures of port and airports and resultant backlogged operations. Storm debris clearance.
Sea level rise and storm surges	Erosion of coastal roads and railroad infrastructure, disruption for transport networks and activities situated in low-lying areas. Higher tides for port facilities and potential disruption of road/rail access to ports. Potential for flooding exacerbated by inadequately dimensioned drainage facilities. Exposure of low-lying coastal airports to storm-surge damage and flooding. More frequent and/or permanent inundation of transport facilities in low-lying areas. Corrosion of steel and concrete materials. Increased scour for defensive structures and bridges.
Change in the frequency of winter storms	Less or more ice or snow for all modes.
Lightening	Disruption of power supply (overhead catenaries, lights, ICT, etc.)

The following sections describe climate-related impacts on the different types of transportation asset systems: roadways, railways, airports, ports and inland waterways. For roadways, this report considers pavements, earthworks, and bridges (including culverts), while for rail it considers tracks, ballast and substructure. For airports this report looks at airport pavements and terminals whereas for ports, it looks at docks, protective elements and sea-side construction. Although this report does not detail them here, both airports and ports include a number of buildings, electrical-mechanical engineering related facilities and machinery (e.g. cranes in ports) that are essential to their functioning; these are noted where appropriate. Each asset type is analysed at the level of separate sub-components where relevant; for example, pavements can be separated into asphalt, base and sub-base layers, while bridges in deck, substructure and superstructure. There are of course common elements – especially as concerns geotechnical substructures. These are examined once and referenced later as necessary.

The following sections discuss change impacts to transportation assets on two levels. The first level refers to the type of infrastructure considered (roadway, railway and so on); appropriate disaggregation is offered on a case-by-case element and component. And the second level refers to the particular climate change parameter considered. Table 2.4 summarises the infrastructure assets examined and their components.

Table 2.4. **Transportation asset types, elements and components**

Asset	Elements	Components (where applicable)
Road	Pavement	Flexible pavements • Asphalt layer • Base • Sub-base • Sub-grade Rigid pavements • Concrete slab • Base • Sub-base • Sub-grade
	Bridge	• Deck • Superstructure • Substructure
	Tunnel	• Lighting • Emergency communications • Monitoring equipment, ventilation equipment
	Earthworks	• Slopes • Embankments
	Drainage	• Culverts
	Signage, power, lighting, ITS and communications	• Signage • Variable messaging signs • Light masts • Embedded sensors • Cameras and monitoring equipment

Table 2.4. **Transportation asset types, elements and components (continued)**

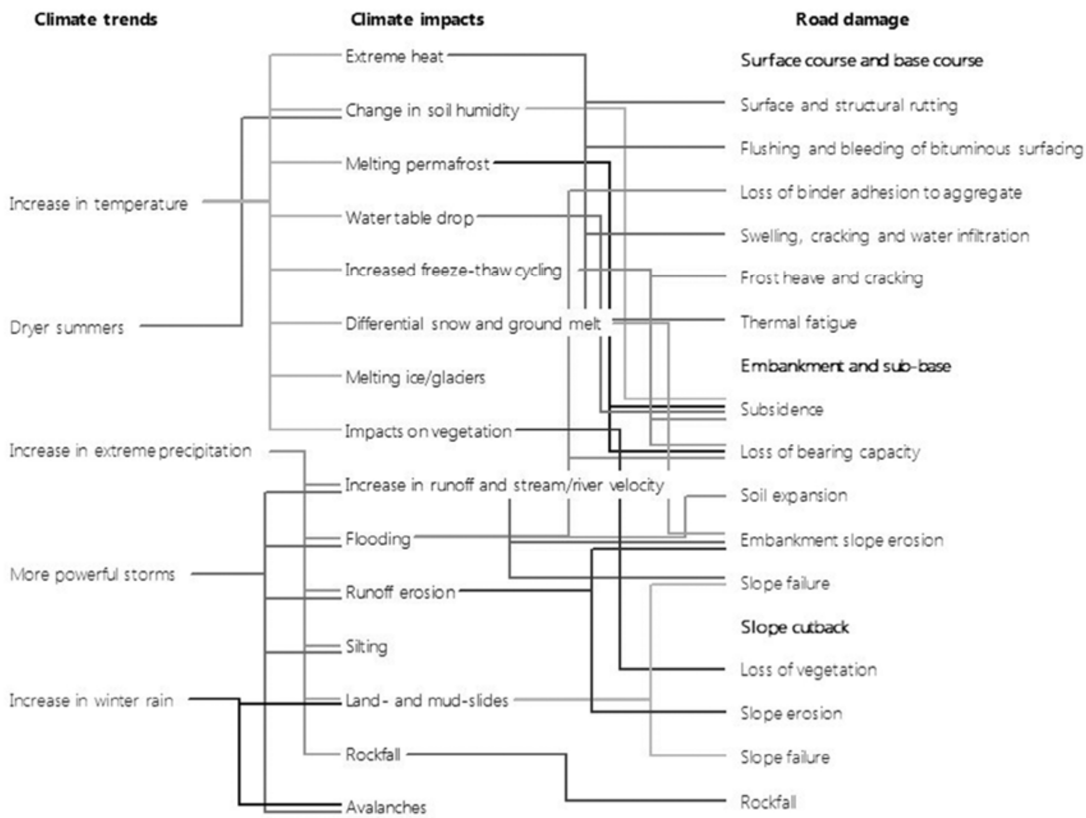
Asset	Elements	Components (where applicable)
Railway	Track	• Rail • Slippers • Joints • Ballast • Switches
	Substructure	• Railbed
	Earthworks	• Same as roadway
	Power and signaling	• Overhead catenaries • Signaling equipment
	Drainage	• Culverts
Airport	Pavement	• Same as roadway
	Earthworks and flood protection	• Dykes and protective walls for coastal and low-lying airports
	Terminals and buildings	• N/A
	Drainage	• Culverts • Pumping equipment (low-lying coastal facilities)
	Equipment	• N/A
Port	Docks and wharfs	• N/A
	Terminals and buildings	• N/A
	Equipment	• Cranes • Mobile cargo handling equipment
Inland waterways		• N/A

Roadway infrastructure

The road network is comprised of strategic, high-volume primary arterials and motorways that carry a substantial amount of traffic and an extensive network of lower-volume secondary access roads that are necessary for door-to-door travel. In nearly all instances the primary networked is paved with asphalt or concrete as is a significant portion of the secondary network though in many remote regions, roads may be gravel-surfaced or even seasonal in nature as is the case with ice-roads in northern latitudes.

As road infrastructures are constantly exposed to weather, their component materials are evidently affected by weather phenomena such as heat, rain, and wind. Furthermore, hazards can have direct impacts on the structural integrity and functionality of road infrastructures. These impacts are multiple, oftentimes simultaneous and can cumulatively lead to unavailability, damage and potential failure – though some climate impacts may be positive. Figure 2.2 outlines the links between climate trends, climate stressors and road damage. This section investigates particular types of road infrastructures including pavements, earthworks, bridges and tunnels and their anticipated degradation as a result of climate changes and hazards.

Figure 2.2. **Indicative climate trends, impacts and damages for roadways**



Source: Adapted from Parriaux, 2012.

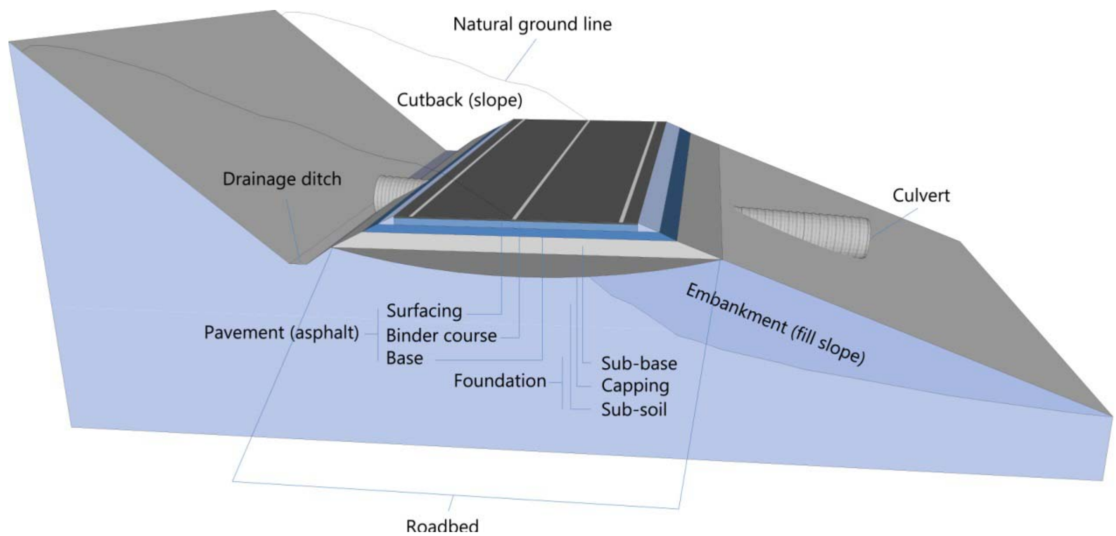
Pavements

Pavements are most susceptible to extreme heat and moisture/precipitation levels. They are also exposed to damage and blockage from landslides and rock fall. Depending on the pavement type (flexible vs. rigid) weather impacts may differ. Flexible (asphalt) pavements are formed by a number of layers shown in Figure 2.3; the upper layer (surface course) is the asphalt layer, followed by the base and sub-base layers.

The service life of road structures (pavement and foundation) typically ranges from 40 to 50 years, depending upon its type (Meade and Janisch, 2003; Refsdal and Johansen, 2008) except for long-life concrete or polymerised pavements whose service life may be extended to 60 years (Hall et al., 2007). However, these lifetimes assume that the surface will be maintained and rehabilitated in intervals of 15-30 years (Li and Kaini, 2006; Refsdal and Johansen, 2008). Figure 2.4 presents a typical pavement life cycle under good maintenance practices and with periodic refurbishments and illustrates how this life cycle might change in areas where climate impacts lead to more rapid deterioration and earlier maintenance and refurbishment requirements. Not all regions, however, would be exposed to the same changes in life cycle and maintenance regimes. In the Province of Quebec, Bilodeau et al. (2013) find that pavement structures could see a 28% reduction in service life over current pavements with expected changes in climate. Modelling from Australia, on the other hand, indicates that under warmer and dryer conditions expected with climate change, pavement performance might in fact improve leading to fewer maintenance interventions and potentially longer life (Taylor and Philp, 2015).

Changes in temperature (higher average temperature, increase in the frequency of hot weather extremes and warm summer days, warmer winter temperatures and an increase in the number of freeze-thaw cycles) affect asphalt pavements in a number of ways as described below.[3]

Figure 2.3. **Typical (asphalt) road components: Pavement and foundation**



Higher temperatures: Flexible pavements

The increase in maximum pavement temperatures and the duration of hot spells increases the potential for asphalt deterioration via rutting and lateral displacement of asphalt under dynamic loading – especially on high traffic roads (see Figure 2.4). Higher ultraviolet radiation prematurely ages asphalt pavements and makes them brittle (less flexible) thus also contributing to asphalt surface cracking initiation and propagation which can initiate water damage to lower layers (Figure 2.5). These phenomena reduce comfort in the most benign cases or lead to loss of vehicle control and crashes in the worst cases. One potential remedy is to resurface with more rut-resistant mixtures or thin rut-resistant surfaces as temperatures increase. Alternatively, using higher temperature binder grades or binders that age more slowly when resurfacing could also reduce heat damage to pavements. However, in the case of increasing extreme temperatures, historical guidance on the specification of binder grades may no longer be adequate. Prolonged hot and dry conditions may also result in subgrade shrinkage and loss of uniform bearing capacity.

Another approach may be to increase the use of binder polymerisation. The latter strategy, though more expensive than current pavement materials, could increase the life of the wearing course beyond the typical ~20 year refurbishment cycle – and up to 40 years (ITF, 2008) . This may decrease the incidence of heat-related damage but could extend the life of some pavements into periods where more frequent winter precipitation or more extreme precipitation may become the norm. Both of these phenomena are potentially damaging to pavement as described below.

Figure 2.4. **Indicative changes in pavement life cycle and maintenance regimes under negative impacts from climate change**

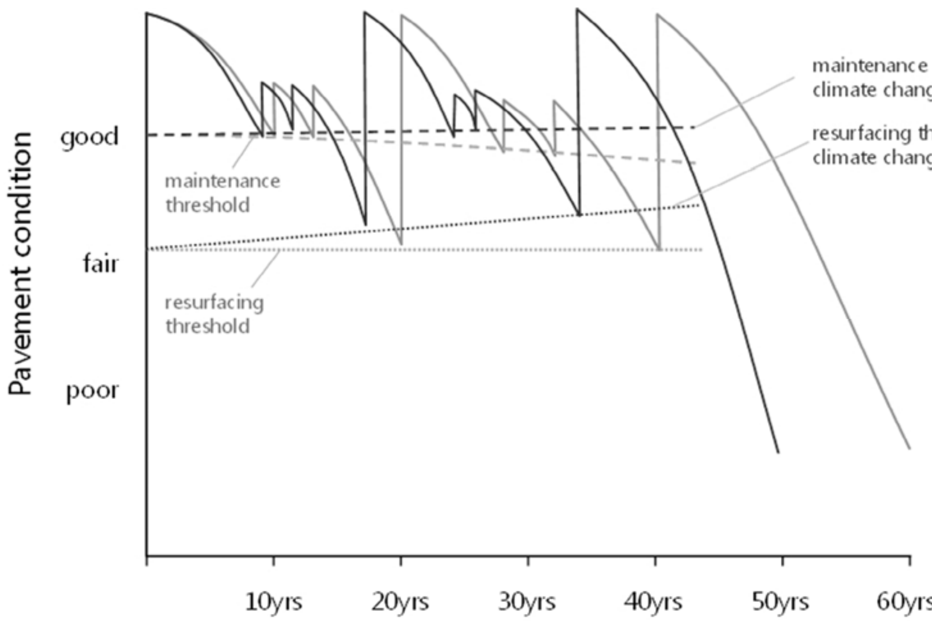


Figure 2.5. **Heat damage to asphalt pavements: Rutting and cracking**

Source: Left © W. Burda; Right © Oregon Department of Transportation.

Higher temperatures: Rigid pavement

Rigid (concrete) pavements consist of concrete slabs lain over the base, sub-base and sub-grade layers (replacing the asphalt surfacing, binder course and base illustrated in Figure 2.3). Traffic loads are taken on by the slabs and distributed more directly to the sub-base and sub-grade layers. Concrete and other rigid pavements are susceptible to heat warping, temperature-related curling and transverse crack formation (Willway et al., 2008). In general, concrete slabs are resistant to moisture effects but during extreme heat events, concrete pavements may experience "blow-ups" as moist base layers expand (see Figure 2.6).

Possible remedies include better accounting for the coefficient of thermal expansion and drying shrinkage for concrete, shorter joint spacing to reduce warp stress, using thicker slabs and/or less rigid base materials. Installing flexible expansion joints between slabs can also reduce the risk of blow-ups during extreme heat events. As with flexible pavements, drought conditions may give rise to damaging subgrade shrinkage and subsidence.

Figure 2.6. **Concrete slab pavement blow-up due to elevated heat and base humidity**

Source: © City of Champaign-Urbana.

An increase in average and extreme warm temperatures may have an impact on the scheduling of construction and maintenance activities as well. Dunne, Stouffer and John (2013) found that heat stress has already reduced labour capacity for outdoor work (all sectors, globally) during peak months by 10% from 2010 levels. This could increase to a 25% to 60% loss of labour capacity during the warmest months respectively for the RCP 4.5 and RCP 8.5 scenarios.[4] Some operations may have to be switched to night-time (possibly entailing higher costs) but warmer weather may also allow for more winter scheduling of work – unless winter moisture and precipitation levels render these operations impossible.

Warmer average winter temperatures and warmer winter extremes

Impacts of warmer average winter temperatures and warmer extreme cold temperatures are mixed depending on the context. Generally, warmer average winter temperatures and warmer winter extremes may *reduce* the depth of winter frost and possibly *reduce* the incidence of winter frost heave which can lead to pavement fatigue and local failure (e.g. potholes). This might entail a reduction in de-icing efforts, a relaxation of frost depth protection measures in some instances and a raising of low temperature asphalt binder grades. On the other hand, though evidence is mixed, warming winters could in some areas contribute to *increased* freeze-thaw cycling as temperatures rise to around the freeze point. This could lead to an *increase* in frost heave-induced damage to pavements. This would entail adjusting binder grades for flexible pavements and mitigating freeze-thaw cycling impacts on rigid pavements, especially as concerns the treatment of joints. More freeze-thaw cycling would also require more frequent de-icing applications in order to prevent loss of skid-resistance crashes. Because thaw-saturated soils lose bearing capacity, changes in the thaw cycling regime may also require more frequent or prolonged load restrictions for thawing roads entailing economic losses for commercial transport operators.

In northern latitudes, warmer winters (and summers) will lead to deeper permafrost melting resulting in damaging heaving movements that will impact the usability and safety of roads (see Figure 2.7). Many communities and industries in northern regions depend on winter access by ice roads and frozen rivers that have a greater load-bearing capacity than the oftentimes unpaved summer roads (if any). Warming trends have already reduced the yearly availability of seasonal ice-roads and this loss is likely to accelerate under warming trends (Stephenson, 2016). This results in increased access costs as alternative infrastructure will have to be upgraded or built, or loss of access and ensuing economic losses (Sawyer, 2014; Borkovic, Nolet and Roorda, 2015).

Figure 2.7. **Melting permafrost: Heave damage to roadway**

Source: Natural Resources Canada.

Increases in average and extreme precipitation, and flooding

Increased moisture levels have a damaging effect on pavement. Increased water presence strips aggregates from their binding material in the asphalt layer and contributes to its rapid deterioration. Higher average levels of precipitation reduce the structural carrying capacity of pavements due to higher moisture saturation levels. Ensuring positive cross-slopes can help with water evacuation thus reducing these impacts. Intense precipitation and storm surge can also lead to hydraulic-induced failures of embankments and foundations (see below) resulting in a total loss of pavements. Drainage and foundation-failures are the main source of climate risk for roads in regions experiencing higher average and extreme precipitation trends and coastal flooding.

More intense rainfall also has an impact on road safety. In order to improve visibility and reduce the incidence of crashes caused by loss of skid resistance (aquaplaning), many jurisdictions are investing in porous asphalt pavements (Stipanovic et al., 2015). These pavements, however, are generally susceptible to freeze-thaw damages outlined above unless properly drained.

Impacts from intermittent flooding can be mitigated by installing, upgrading and maintaining effective sub-drainage systems. Stream, river and coastal (wave and storm-surge) flooding can temporarily make roads unavailable. These phenomena can also cause kinetic impacts that result in partial or complete destruction of the pavement layer (see Figure 2.8). Prolonged submersion of roadways threatens the stability of embankments and foundations. These risks can be mitigated by increasing the use of bound materials in the base and foundation layers, elevating the roadway, or re-siting roads away from flood-prone areas. The latter two options are especially expensive.

Many countries have extensive networks of unpaved gravel roads, especially in rural areas. These roads typically carry light traffic but in many instances represent crucial links to isolated communities. These roads are especially vulnerable to increases in average and extreme precipitation levels (Aursand and Horvli, 2009). Changing climate regimes may require the upgrading of some of these in order to avoid excessive maintenance costs which will entail considerable upfront costs. In some cases, upgrading may be uneconomic entailing degraded access conditions and loss of viability for certain communities.

Figure 2.8. **Hurricane Sandy storm-surge damage on Highway 12 in North Carolina**

Source: © NCDOT Communications.

Relevance of climate change time-scales to adaptation of road pavements

Estimation of the service life of pavements and particularly their surface layer is directly related to the timing of potential climate change impacts. Since the life cycle of the pavement *surface* (surfacing and binder course) is relatively short (15-20 years), it seems likely that the normal scheduling of maintenance and resurfacing will allow for flexible adaptation to changing climate regimes. In many cases, decisions regarding which adaptation actions to deploy in response to changing temperature or precipitation trends can be made during the normal life cycle of road pavements. In some cases, accelerated deterioration, most likely linked to hydraulic damages, may require advancing certain maintenance and refurbishment actions.

Earthworks and geotechnical structures

Earthworks and geotechnical structures include the road/rail foundations (embankments) and corridor configuration (slopes and cuts) illustrated in Figures 2.3 and 2.16. These are typically soil- and sand-made, and are highly prone to inundation and hydraulic damage. Indeed, changes in precipitation intensity and frequency are more likely to affect structural integrity of roadway earthworks including road foundation (the substructure and sub-grade layers), and slopes than the pavement itself (Keller et al., 2011) (Parriaux, 2012).

Potential climate impacts on these structures are numerous. For example, erosion of road-side slopes can result from rainfall and water runoff along slopes (Xu et al., 2009). Slope stability (and the possibility of landslide and rockfall occurrence), is related to the groundwater level and degree of saturation[5] fluctuations in the slope (Dehn et al., 2000). Increased moisture reduces the cohesion and therefore the strength of soils (Samtani and Nowatzki, 2006). Along the same lines, intrusion of water in the road foundation through groundwater level rise or damage in the upper pavement layers (combined with increased rainfall), could also lead to erosion and saturation phenomena, which can again weaken road foundation. As with pavements, repeated or prolonged flooding of earthworks increases the risk of serious damage. Micro-flooding (e.g. localised impoundments) is often not expressly accounted for in earthwork design yet these relatively widespread and potentially damaging events are likely to increase in number with an increase in average and extreme precipitation (Polemio and Lollino, 2011). Weakened earthworks and foundations lose their bearing capacity and in extreme cases can lead to foundation washout or collapse (see Figure 2.9). In these instances, improving drainage and/or introducing hydraulic binding agents into foundation and earthwork materials may help.

In areas likely to experience hotter and dryer conditions and extended droughts, the structural integrity of earthworks may degrade due to desiccation (water removal) in soils containing fines (for example clay). In higher altitude mountainous areas and northern latitudes, increased permafrost melting and dynamic soil fluctuation can lead to loss of slope and cut cohesion resulting in rock-fall.

Figure 2.9. **Foundation washout and collapse**

Note: US Route 101 in Oregon and Oldbury rail Viaduct, UK
Source: Left, © Visitor7; Right, © David Stowell.

In addition to water-related climate change impacts, slopes and road foundations may be affected by changes in the frequency of freeze-thaw cycles. Increased freeze-thaw cycling reduces the effective stresses[6] or cohesive capacity of the materials forming earthworks. Another impact, also related to both weather and temperature, is the change in vegetation along slopes and embankments. While lack of vegetation (in cases of extreme dryness) could negatively impact slope stability (and lead to visibility-reducing and dangerous fires), rapid growth of plants may reduce the operability of a road (for example by limiting road visibility) and increase maintenance needs.

Extreme weather phenomena could be another source of earthwork degradation. Intense winds and severe storms for instance can cause rapid erosion of road-side slopes and unexpected landslides (Keller et al., 2011), while flooding and storm surge could lead to earthwork failure, particularly when drainage infrastructures and culverts are inadequately dimensioned.

All of the impacts outlined above hold true for earthworks and geotechnical components for all transport infrastructure, not just roadways. In addition, transport network planning for adaptation must account for the resistance of geotechnical components *outside* of the direct responsibility of many transport authorities. In particular climate change-related impacts on levees and seawalls that lead to breaches will have knock-on effects on transport systems and earthworks.

Relevance of climate change time-scales to adaptation of earthworks and geotechnical components

Because geotechnical elements and earthworks are typically longer-lived than pavements (or ballast, in the case of rail corridors), these infrastructure components will be exposed to changes in climate and thus more proactive planning may be required, especially in areas likely to experience increases in average and extreme precipitation and in coastal areas prone to storm damage and flooding.

Bridges

Bridges are probably the most complex and sensitive roadway infrastructure element. Because of their strategic role in spanning otherwise impassable landscape elements (streams, rivers, coastal waterways, canyons, etc.) their failure may result in large detour-related time losses. Sometimes, they may represent the sole link to communities, in which case their loss imposes extreme hardship on inhabitants.

Bridge design (and cost) is usually related to length, materials used, foundation capabilities and intended traffic capacity (Ryall et al., 2000). Because bridges represent relatively large-scale and strategic capital investments, their typical design life exceeds 60 years (details are presented in Table 2.5) and their actual useful life may extend many more years (or decades in some cases). For instance, nearly 30% of the road bridge stock in the United States was over 55 years old in 2013 (FHWA, 2013). This implies that, unlike other roadway elements such as pavement surfaces whose service life is approximately 20 years, bridges constructed today will almost certainly be exposed to future climate change. Furthermore, many of the bridges in use today were constructed using engineering standards that reference meteorological and climate conditions that are less and less representative of current (and likely future) conditions (Meyer et al., 2014; Nemry and Demirel, 2012). Bridge materials (concrete, steel, timber) have different properties with respect to temperature, water and other climate variable, and thus concrete and steel bridge components should be considered separately.

Table 2.5. **Service life for typical bridge components**

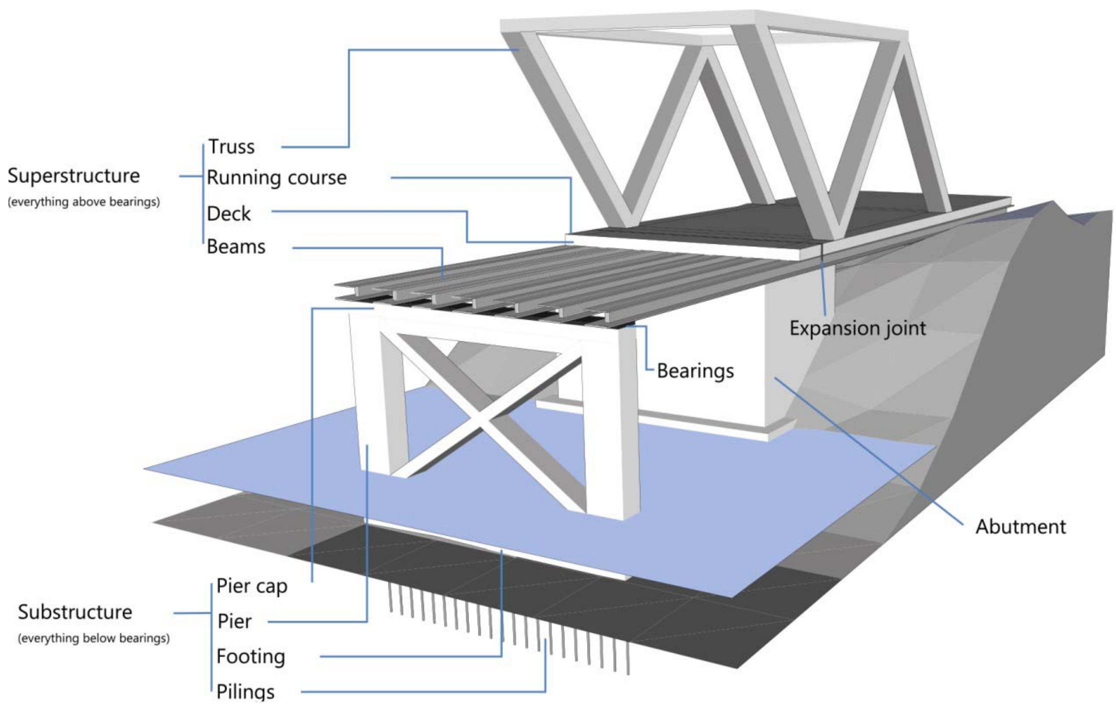
Component	Average service life
Deck	30-50 years
Superstructure	60-80+ years
Substructure	60-80+ years

Source: Compiled from Russel et al., 2004; Sohanghpurwala, 2006; Kaini and Li, 2006; Liang et al, 2009.

Bridges are made up of three major components: deck, superstructure (everything above and including the bearings) and substructure (all elements below the bearings). The deck is the roadway, railway or pedestrian-way surface of a bridge; decks are either concrete slabs or steel plates, stiffened in one or two directions (orthotropic decks) (Ryall et al., 2000), while their surface can be either asphalt or concrete. The superstructure includes the bridge spans, which support deck loads and connect substructure components. The superstructure can be made of concrete, steel or wooden beams, steel trusses, cables or other load bearing or load-distributing elements, depending on the bridge type and material used. In some cases, superstructures and decks are combined in a single component (for example in T-beam structures). Substructure components are those elements that support the superstructure and deck and distribute loads to the ground; these are abutments, piers and their foundation (see Figure 2.10). Most substructure elements (abutments, foundation) are concrete but piers could also be steel or composite (steel-concrete) – foundations usually include spread footings or piles.

Changes in average and extreme temperature will affect both the concrete and steel components of a bridge. Thermal expansion of steel elements or thermal mismatch between cement and aggregates of concrete elements can lead to deterioration which can weaken the structural strength of those elements (Ryall et al., 2000). Increased average and extreme temperatures can also result in a change of the thermal strain stress behaviour of structures which may lead to changes in performance. Tensile stresses in particular may display new and potentially damaging values and should be monitored. Adaptation efforts may include focusing on reducing heat absorption by structures by, for example, lighter, heat-reflective coatings (Santillán, Salete and Toledo, 2015).

Figure 2.10. **Typical bridge components**



Changes in average and extreme temperature will affect both the concrete and steel components of a bridge. Thermal expansion of steel elements or thermal mismatch between cement and aggregates of concrete elements can lead to deterioration which can weaken the structural strength of those elements (Ryall et al., 2000).

Increased humidity and water infiltration, in conjunction with increased temperature, accelerates chemical deterioration of both steel and concrete components. Steel corrosion is a result of rusting due to moisture, while concrete corrosion can be chloride or carbonation induced (Figure 2.11). Increased atmospheric CO_2 concentrations accelerate carbonation damage to concrete and thus potentially expose steel reinforcing elements to corrosion. Carbonation-induced damage risks may rise significantly as CO_2 concentrations increase – (Stewart, Wang and Nguyen, 2012) find that these may increase by 16% by 2100. Concrete carbonation combined with expansive corrosion of steel reinforcement elements result in concrete cover cracking and spalling and a loss of structural capacity (Stewart, Wang and Nguyen, 2011). Since the increase in atmospheric CO_2 concentration is one of the most robust and predictable climate-relevant trends, there is a strong likelihood that transport authorities will see (and should plan for) more rapid carbonation-induced damages to concrete infrastructure. Increases in concrete thickness, improved concrete mixes and the application of coatings and barriers can help but will increase the cost of construction and maintenance (Stewart, Wang and Nguyen, 2012).

Chloride-induced corrosion is a significant threat to submerged or partially submerged concrete/steel infrastructure in coastal areas. It is not clear that climate change will modify the chlorination mechanisms though sea level rise and sea water infiltration of fresh water coastal bodies may see an increase in the exposure of concrete infrastructure to chloride-induced corrosion (Wang et al., 2011).

Figure 2.11. **Steel and concrete bridge component corrosion**

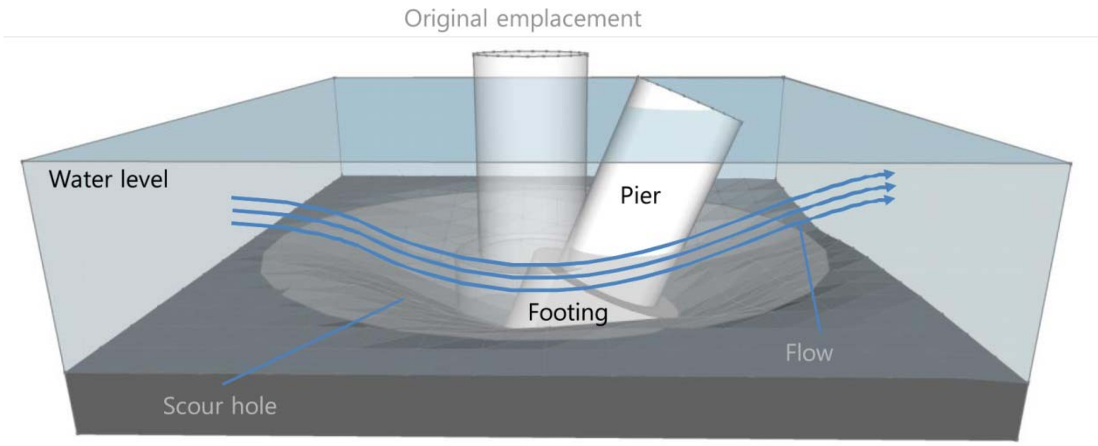
Source: Photos © Achim Hering.

Increased precipitation affects bridge components in multiple ways: the deck and superstructure may be damaged from water intrusion which will cause further corrosion and deterioration, particularly if the bridge's drainage system is not designed to absorb additional water volume. As for the substructure, rainfall, and storm flooding could alter water level and flow under the bridge, as well as soil properties in the vicinity of bridge foundation. In particular:

- Changes in water flow strength and level increases potentially damaging dynamic loading on submerged structures including abutments and piers (Radomski, 2002).
- Turbulent high velocity water flow around submerged bridge components can scour surrounding foundation and bank material leading to loss of structural support (Figure 2.12) (Radomski, 2002).
- Saturation in the vicinity of the bridge foundation may negatively affect the soil's effective stress and therefore its loading capacity; in such a case the soil fails by sinking or shifting and causes structure movement or damage.

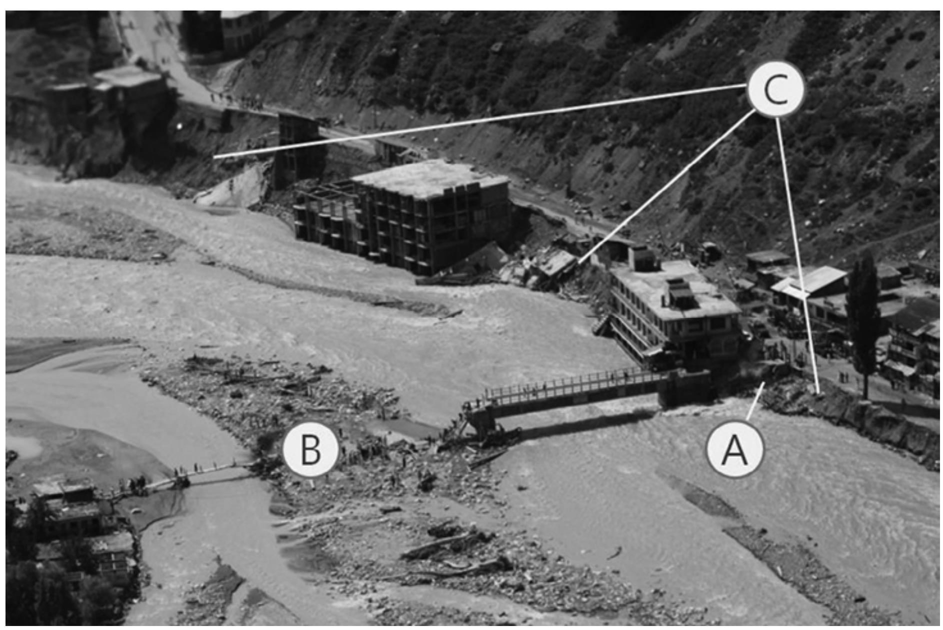
Evidence from the United States indicates that 62% of over-water bridge failures are due to hydraulic causes (Cook, Barr and Halling, 2014). Wright et al. (2012) project that 10-20% of the current US over-water bridge stock could be at-risk for significant hydraulic damage by 2050, increasing up to 25% by 2100.

Figure 2.12. **Bridge pier scouring: Damage and displacement**



Hydraulic events such as scour and dynamic loading can lead to single-point failure or, in extreme cases, to multiple-point failures that compromise not only the integrity of the bridge itself but its approaches as well (Figure 2.13).

Figure 2.13. **Monsoon flooding-triggered bridge and road damages in Pakistan (2010)**



A. Scour-induced loss of embankment and abutment support.
B. Scour and dynamic loading loss of piers.
C. Scour-induced loss of embankment and foundation of approach road.
Source: Horace Murray.

Finally, extreme wind intensity may render bridges inaccessible for safety reasons and may cause damage when wind loads are exceeded. Climate change impacts on bridges are summarised in Table 2.6.

Table 2.6. **Climate change impacts on bridges**

Climate change variable	Impact to…	
	Concrete components	**Steel components**
Temperature changes	• Upper deck surface deterioration (as in pavements)	
	• Damage due temperature difference between cement and aggregate	• Damage due to thermal expansion of steel components
Increase in precipitation - moisture	• Chloride or carbonation induced corrosion • Substructure scouring • Foundation failing due to soil saturation	• Corrosion due to rusting.
Increase in atmospheric CO_2	• Carbonation induced corrosion	
Sea level rise	• Substructure scouring • Foundation failing due to soil saturation	• Corrosion due to rusting.
Extreme weather events	• Damage – collapse of structure	

Culverts and ditches

Culverts are arguably as critical, if not more critical, than bridges for ensuring high-quality transport services because they are both more common and more susceptible to damage and catastrophic failure and thus represent many more potential network failure points. Generally hidden and invisible to most transport system users, culverts play an essential role in maintaining the structural integrity of transport infrastructure. Placed wherever transport infrastructure cross drainage slopes, or where drainage is necessary from longitudinal drainage ditches, culverts pass water from one side of an infrastructure to the other (Figures 2.2 and 2.16). This prevents water from ponding on the upstream side (and thus weakening earthworks) or passing over and damaging road pavements, rail permanent ways or airport runways and taxiways. Ensuring adequate drainage also improves safety and improves user comfort. Ditches collect water from infrastructure and surrounding slopes and allow it to either percolate into the soil or be evacuated by subsurface drainage culverts. In urban areas, open ditch-culvert systems are replaced by extensive closed underground storm water drainage systems.

Culverts are relatively long-lived infrastructure made either of corrugated sheet metal piping (less expensive), high density polyethylene or polyvinyl chloride pipes, or of concrete (concrete box culverts – more expensive). The service life of culverts should at least match the service life of the infrastructure in which it is embedded since culvert replacement can completely disrupt traffic and lead to traveller time losses (Schall et al., 2012). Perrin and Jhaveri (2004) report that US transport agencies assumed lifetimes of 50-100 years for concrete culverts, 30-100 years for plastic culverts and 30-50 years for corrugated metal pipe culverts. As such, existing culverts will be increasingly exposed to climate conditions for which they were not designed and new culvert design specifications will have to account for climate change over their lifespan.

Figure 2.14. **Road damage from culvert failure and washout**

Source: Left, © Seattle Municipal Archives; Right, © Daniel Case.

Once installed, culverts generally prompt little attention and making the case for continued and proactive maintenance has not necessarily proven easy in many jurisdictions, especially in light of budgetary constraints (Perrin and Jhaveri, 2004; Kalantari, 2011). Culvert failure, on the other hand, typically elicits significant attention as it implies road and track closures and significant repair and re-routing costs (see Figure 2.14).

Culverts can fail in multiple ways. Both steel and concrete culverts are susceptible to corrosion (rust for steel and carbonation for concrete). This corrosion weakens the structural strength of these materials (leading to collapse in some cases) or allows water to seep into the surrounding structural soil and initiating erosive damage. In fact many culvert failures can be traced to failure of the soil-pipe structure (Tenbusch, Dorwart and Tenbusch, 2009; Schall et al., 2012). This failure is typically initiated in three ways (Tenbusch, Dorwart and Tenbusch 2009; 2013):

- when water enters into areas from which it was originally excluded (in the case of seepage or piping)
- when extreme flows lead to scouring and erosion of embankments and structural soils in the inlet area (including behind protective wings) and at the outlet
- because of debris blockage, pipe collapse or hydrostatic pressure.

Increased average precipitation and extreme precipitation levels will have an impact on culvert performance and these changes should be incorporated into culvert design. Culverts are designed to handle peak flows that are likely to be encountered in their location. The determination of these peak discharge rates is based on methods[7] that either directly or indirectly incorporate factors such as historic climate variables (24-hour precipitation, intensity-density-frequency curves and precipitation distribution input values), slopes and size of the catchment area. Correction factors accounting for lakes and other impoundments, the degree of vegetative cover or soil permeability or for climate change can be applied to these calculations (Kalantari, 2011; Meyer et al., 2014).

As it would be uneconomic to build culverts to handle all possible extreme precipitation scenarios, a decision is typically made on the return period to plan for in terms of the amount of flow to be handled in a given period of time. If climate change leads to more intense precipitation extremes, existing culvert design may prove inadequate leading to ponding on the upstream side and prolonged high-velocity flows. Both of these may initiate the type of failure points outlined above.

Climate change may have an impact on other variables besides precipitation in the peak flow calculations for culverts. Soils typically absorb a significant amount of precipitation with the remaining fraction working its way into the waterway network. Climate-related changes to soil permeability and absorption rates will change the precipitation-runoff factors that are typically built into culvert size calculations. For example, since highly desiccated (and compacted) soils lose their absorptive capacity, extreme precipitation events (which are predicted to increase in places even where average levels of precipitation will decrease) will result in higher rates of runoff to be handled by culvert structures (Meyer et al., 2014). A similar loss of soil permeability occurs in the case of winter rains on frozen (or near-frozen) soils which would lead to elevated runoff and culvert flow duration (Kalantari, 2011).

Several options exist to address potential culvert damage from extreme precipitation. These include re-sizing the dimension of the culvert, protecting embankments from scour by adding headwalls, side wings or endwalls or by preventing excessive scour damage at the outlet. These decisions are typically taken on the basis of first-order hydraulic considerations. However, many soil-pipe failures are in part the result of debris accumulation and the ensuing loss of culvert capacity. It may very well be that a properly dimensioned culvert may still fail if wood debris and sediment have reduced its effective diameter leading to ponding, deformation and scour dynamics that were unforeseen. Culvert performance is perhaps more a result of adequate maintenance regimes than adequate design. This is one area where authorities often lack budget as well as adequate knowledge pertaining to the condition of their culvert stock.

Tunnels

Tunnels and other underground structures are often designed to last for 100 years and are scarcely affected by weather conditions (Schiessl et al., 2004). However, certain weather-related hazards and particularly flooding may render the tunnel temporarily unavailable or damage the structure and the tunnel's equipment (Bobylev, 2009). In some cases, a rise in underground water level (due to extreme rainfall or storm surge – see Figure 2.15), could affect a tunnel's structural integrity (Bobylev, 2009). Tunnel and underground flooding will also have an impact on networks and infrastructure (power, telecoms, signaling in the case or public transport and rail) which can render essential services inoperable for extended periods of time. Also, temperature changes may impact the operation and performance of a tunnel's ventilation system (Bobylev, 2009).

Figure 2.15. **Flooded NYC tunnel due to Hurricane Sandy storm surge and infiltration**

Source: Left and right, © New York City Metropolitan Transit Authority.

Railway infrastructure

Railway networks are of mixed vintage across many countries with many components (bridges, tunnels, embankments and cuts) dating back to the 19th century. These components were designed for trains not capable of operating over more than very shallow gradients. Consequently, rail alignments of that vintage (and up through the 20th century) required extensive use of slope cuts and embankments to level the track profile. Though generally stable, these earthworks of uncertain quality and of sometimes rudimentary design (compared to modern standards) are susceptible to failure, especially under a changing climate and hydrologic regimes. Rail earthworks are similar in nature to those supporting roads and they share many of the same vulnerabilities. They are vulnerable to changes in precipitation and humidity patterns, flooding and water ingress. In coastal areas, they are vulnerable to wave action, storm surges and flooding (DfT, 2014) (see Figure 2.16). Finally, as with road maintenance, increased summer temperatures may limit the time available for track maintenance and this may not be compensated by milder (but wetter) winter temperatures in the Northern Hemisphere. Due to the need for relatively warm ambient temperatures necessary for stress-free setting of rails, the potential loss of summer maintenance opportunities may have knock-on effects on system performance as discussed further.

Damage to rail earthworks and geotechnical components reduce the bearing capacity of the ballast and tracks which may require reduced train operating speeds. Compromised earthworks pose a risk to the integrity of the track system and in some cases may result in a complete failure of the track foundation resulting in steep repair costs and time losses for passengers. More recent components, including those that make up high-speed rail networks, are built to more exacting standards and in some cases expressly account for potential climate change in their design but remain vulnerable to changes in precipitation patterns and intensities as well as to flooding. Despite commonalities with road infrastructure, rail systems do present unique vulnerabilities relating to the track structure, overhead components and signalling elements; these are addressed in the next section.

Figure 2.16. **Impacts of storm-related embankment scour**

Note: Wave damaged to rail infrastructure on Tillamook Bay Railroad (left) and Dawlish railroad line washout (right).
Source: Left, © Chris Updegrave; Right, © Lewis Clarke.

Railway tracks

The railway track structure consists of rails, sleepers and joints; they form a grid which is itself embanked in the ballast layer consisting of gravel or rocks (Figure 2.17), or is placed over concrete slabs (usually in stations and metro systems). The service life of rail track components for railways in the USA is presented in Table 2.7. Because of their relatively long service life, rail track structure components will almost certainly be impacted by mid- to long-term changes in climate variables. This, coupled with the long-lived nature of rail geotechnical elements and earthworks, makes rail systems especially vulnerable to climate impacts.

The rails themselves are particularly vulnerable to hot temperature extremes and wide temperature amplitudes. This is especially the case for continuously welded[8] rail which is the standard for modern railways. Thermal expansion of welded rails due to temperatures that are significantly above the rail's installation temperature or "anchoring" temperature (rail's neutral temperature) causes compressive stresses which in turn lead to the phenomenon of buckling (Lindgren et al., 2009; Nguyen et al., 2012), shown in Figure 2.18. The vulnerability of rails to track buckling is a function of thermal-induced compressive stress, weakened track and ballast conditions and the dynamic loading of tracks by trains. In a warming climate, it makes sense to select a progressively higher rail neutral temperature during installation and to be particularly vigilant to rail longitudinal, lateral and vertical movement. High temperatures and wide temperature amplitudes (over a short period of time) may also require monitoring and possibly adjusting train loads which may have an impact on network capacity (Nemry and Demirel, 2012).

Figure 2.17. **Typical railway track (with ballast)**

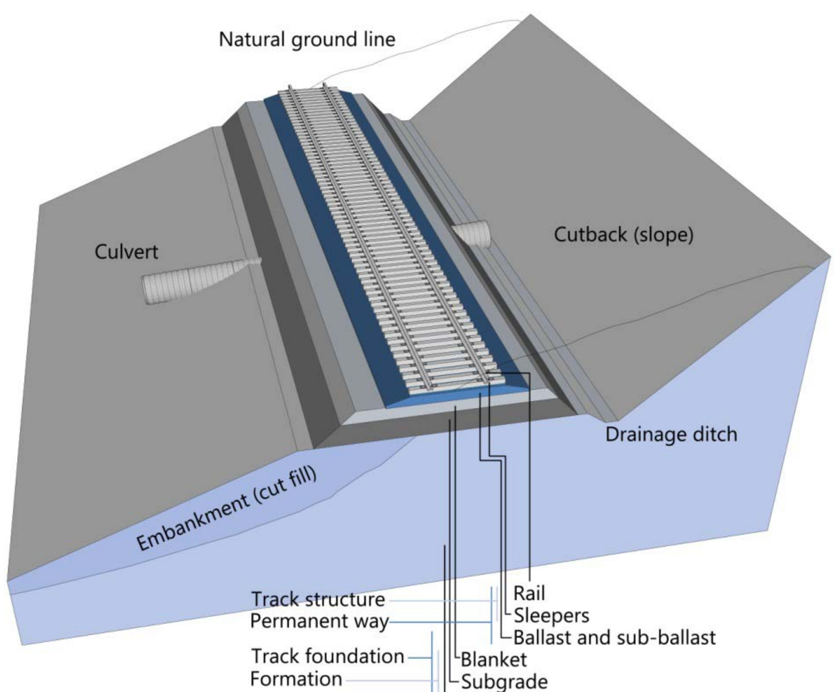


Table 2.7. **Railway component service life**

Component	Maximum service life range
Timber sleepers	35 years
Concrete sleepers	55 years
Continuously welded rails (CWR)	70 years
Bolt joint tails	60 years
Ballast	>60 years

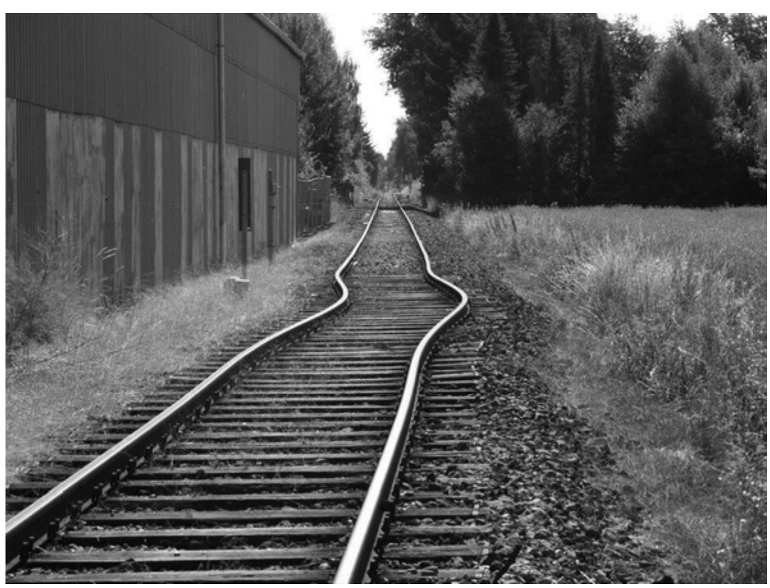
Source: ARUP, 2008.

Railway infrastructure and extreme weather events

As in the case of roadway infrastructure, railway infrastructure such as tracks, earthworks, bridges and tunnels are highly prone to extreme weather phenomena. Flooding in particular, has a long history of causing significant loss of temporary availability and damages to railway infrastructures worldwide. Compared to roadway pavements and foundations, the lateral resistance of track structure permanent ways and their vulnerability to erosion and subsidence is low when exposed to extreme precipitation and associated hydraulic forces.

A change in winter precipitation regimes may give rise to increased wet precipitation in near-freezing conditions. The icing that results in these circumstances can damage overhead catenaries and other rail superstructure leading to delays and loss of service (Figure 2.19).

Figure 2.18. **Heat-induced track buckling**



Source: © ABproTWE.

Figure 2.19. **Ice damage to rail overhead structures and storm-fall on rail tracks**

Source: Left, © Danilo Rozman; Right, © Metropolitan Transportation Authority of the State of New York.

Increases in the incidence of strong storms and extreme wind, combined or not with a CO_2-induced increase in trackside vegetation, would contribute to network disruptions due to more frequent tree fall and other debris (Figure 2.19) unless track-side vegetation is more proactively managed. Finally, as with road infrastructure, an increase in the incidence of drought will impact trackside vegetation and can lead to erosion due to loss of vegetation or more frequent fires that may reduce visibility and damage rail-related structures. These potential impacts should be accounted for in trackside vegetation management programmes.

Urban public transport networks

Public transport services are delivered across multiple modes and infrastructure and as such, they are vulnerable to many of the hazards identified in previous sections. Public transport networks also serve to evacuate populations exposed to extreme weather events and their localised or systemic failures may have knock-on social impacts, especially concerning urban populations that are dependent on public transport services. Beyond the "generic" climate impacts to drainage systems, roads, rails, bridges, tunnels and geotechnical works outlined in this chapter, several public-transport-specific hazards also exist. These relate to flooding of underground subway systems and to public transport operations.

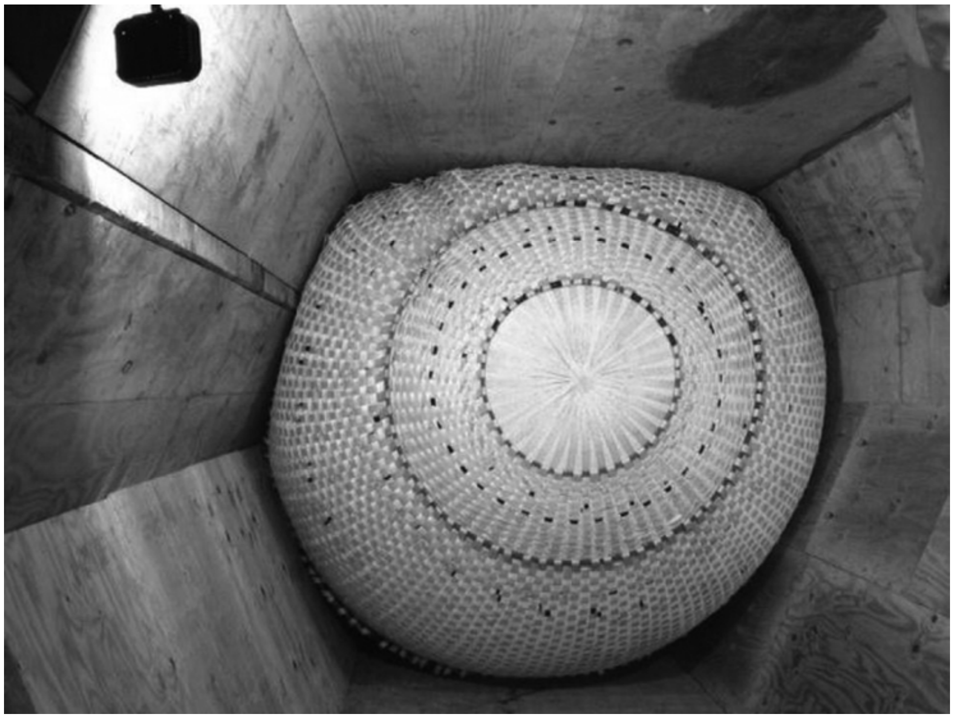
Figure 2.20. **Raised subway entrance to prevent pluvial tunnel flooding, Sun Yat-Sen Memorial Station, Taipei Metro, Taipei**

Source: © mailer_diablo, Wikimedia Commons.

Increased flooding risk, whether pluvial or linked to storm surges and sea level rise, pose particular threats to underground subway systems. These systems are susceptible to flooding which not only temporarily interrupts services, but also entails significant material losses to tunnels, signalling systems and subway stations. Saltwater encroachment can be particularly damaging due to its corrosive effects on electrical systems. Pluvial risk can be mitigated by designing passive rainwater evacuation and management systems, in order to avoid an accumulation of water in the subway, and by installing and maintaining emergency pumping capacity to evacuate water from the subway system. Many subways exposed to frequent or powerful rainfall have raised subway entrances in order to prevent surface runoff flooding (see Figure 2.20). Subway systems are also frequently vulnerable to coastal or fluvial flooding. In those instances, storm gates, temporary storm dams or inflatable tunnel plugs can reduce or prevent floodwaters from propagating through tunnel systems (Figure 2.21).

Public transport services are also susceptible to a number of indirect climate and weather impacts. That can impact operations. As noted above, public transport can serve to help evacuate areas impacted by extreme weather events. They also serve a crucial function in maintaining accessibility in cities during and after extreme weather events. The experience with Hurricane Sandy in New York City highlighted many operational impacts that could be expected to increase as the frequency of extreme weather events increases. These impacts include the need for redundant or excess capacity (provided in part in New York City by bicycles and for-hire van services); the ability to deploy temporary measures to replace the loss of subway services (The Metropolitan Transit Authority, the Department of Transport and the New York Police Department created a pop-up bus rapid transit system overnight to ensure service continuity despite the flooding of several subway tunnels); and the need to adapt operations to the overall loss of accessibility – particularly in light of staff access (many MTA workers were housed in temporary accommodations near depots in order to ensure that they could work their shifts); and degraded command-and-control facilities (Kaufman et al., 2012).

Figure 2.21. **Post Hurricane Sandy trials of inflatable bladder to seal off subway tunnels from flooding**



Source: New York City Metro Transit Authority.

Ports

Global sea level rise poses a threat to all low-lying coastal infrastructures, including roads, rail corridors and airports. Ports, however, by their nature, are especially exposed to sea level rise, estuarine flooding and storms including the damaging effects of storm surges that may exacerbate the impacts of rising sea levels. Port activity is also dependent on good access to the hinterland and thus ports are vulnerable to the potentially damaging impacts of climate change on connecting infrastructure. As with other trade-dependent infrastructure, a changing climate may lead to shifts in global trade patterns (and in particular to trade in agricultural products) which would impact demand for port services. Crucially, many major ports play a critical role in global supply chains – any significant loss or degradation of service would have significant knock-on effects on global supply chain performance.

Port systems are comprised of numerous components and are dependent on multiple service providers and actors. Each of these may be differently exposed to climate hazards implying a need for an overarching framework to better capture port climate vulnerabilities. Stenek et al. (2011), (Becker, et al, 2013) and Scott et al. (2013) propose such a framework to gauge the vulnerability of port system sub-components to climate change. In particular, Stenek et al. (2011) identifies specific vulnerabilities related to navigation, berthing, material handling, vehicle movement, goods storage and transportation. The material impacts of potential changes in climate regimes on each of these sub-systems are, for the most part, not qualitatively different than for the other transport modes already described. Asphalt surfaces are prone to heat damage; port superstructures are exposed to wind damage; wave action and flooding can lead to erosion of embankments and abutments; electrical and other support systems may be prone to damage due to flooding, winds and heat; operations may have to be suspended during heat extremes and concrete materials may be exposed to accelerated rates of carbonation- or chloride-induced corrosion. As with other transport systems, co-sited infrastructure and/or simultaneous or successive climate-related stressors may lead to broad and multi-point failures that may be difficult to predict if each component is analysed in isolation. Port systems do, however, face certain unique hazards related to changes in wave regimes and heights and the impacts of sea level rise and storm surges on breakwaters, quays and protective coastal infrastructure adjacent to port facilities (Becker et al., 2013).

Inland waterways

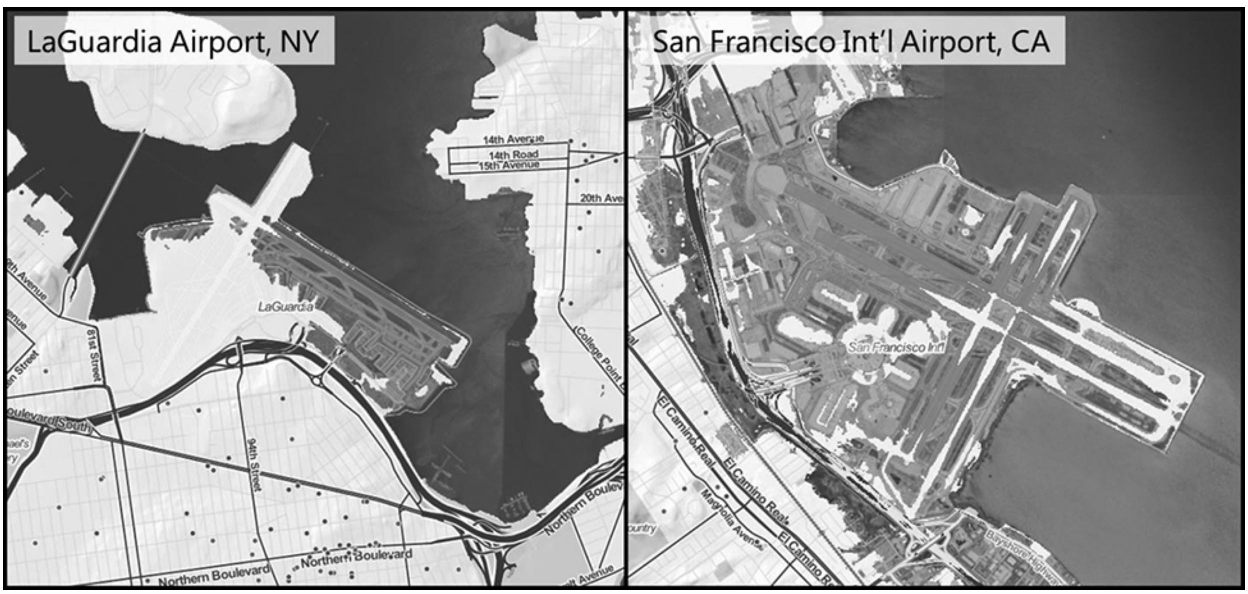
Inland waterway infrastructure, including groynes, training walls, rip-rap, quays, and locks, are exposed to many of the same climate stressors as other transport networks – and in particular to flood-related impacts. The waterway itself may also be subject to temporary incapacity due to winter icing. In addition, inland navigation is highly sensitive to prevailing water levels with low levels imposing lower load factors for vessels and increased costs per tonne transported for operators (Jonkeren, Jourquin and Rietveld, 2011). Projected changes in climate may have an impact on all of these elements with sometimes positive and sometimes negative outcomes for inland navigation.

Inland navigation is dependent on three elements; the river or canal itself including its geometry and hydromorphology, waterway infrastructure that either stabilises the navigable part of the channel or renders the canal operational and the level of water discharge in the waterway (Simoner et al., 2012). Episodes of intense rainfall may lead to elevated water velocities and erosion of river banks, bridge abutments and other infrastructure elements. Changes in river flow characteristics may also impact rates and location of sedimentation which will, in turn, imply changed fairway maintenance practices and may increase dredging requirements. In addition, flooding may lead to short-term river closures due to safety concerns. These types of incidents are projected to increase in the Northern Hemisphere leading to more elevated maintenance costs and time losses for operators and shippers. On the other hand, loss of waterway capacity due to winter icing and ice flows are projected to become much less frequent (Leviakangas, et al., 2012). Given that the latter implies much longer periods of suspension of navigation than the former, this might suggest that overall waterway availability in light of flooding and icing may improve in the Northern Hemisphere though this finding is highly dependent of the local context of different waterway basins (Jonkeren et al., 2013; Leviakangas et al., 2012; Simoner et al., 2012; KLIWAS, 2015).

Inland waterways are highly dependent on rates of water discharge and resultant water levels. Flooding, as described above, can lead to temporary suspension of navigation but low water levels resulting from drought can lead to prolonged loss of capacity of the waterway system or to closures in extreme cases. Rivers and canals can be both rain-fed and meltwater fed. Increases in winter precipitation in the form of rain are expected to lead to higher seasonal discharge rates and in their extreme, these might hamper navigation and damage infrastructure. At the same time, a shift from frozen to wet precipitation will lead to a decrease in the melt-water component of navigable waterways. This implies that springtime and summer water levels may drop as a shrinking ice pack upstream will lead to lower discharge rates. In addition, higher temperatures and decreases in summertime precipitation may further exacerbate low water levels. Projections for both the US and Northern Europe indicate little loss of wintertime capacity but a sometimes significant drop of summertime capacity (and a concomitant increase in operator and shipper costs) due to low water levels (Jonkeren et al., 2013; KLIWAS, 2015). This negative trend becomes especially apparent in the second half of the 21st century (KLIWAS, 2015; Simoner et al., 2012).

Adaptation responses may include low-drought ship designs and other vessel-level technology changes and increased investment in water retention facilities. The former could be deployed over time as conditions warrant and as the vessel fleet naturally turns. Because inland waterway vessels typically have a life of approximately 50 years, planning for fleet adaptation should start now. Longer-term investments in water retention capacity or river infrastructure would entail significant higher investment levels that would have to be evaluated despite a high degree of uncertainty regarding the direction and ultimate scale of changes in water level (ECCONET, 2012). At the same time, uncertainty remains regarding future adaptation costs for competing networks like rail and road that could carry at least some of the goods transported by inland waterway (Jonkeren, Jourquin and Rietveld, 2011) .

Figure 2.22. **Storm surge and flooding vulnerability for coastal airports**



Note : Potential inundation for 91 cm (3ft.) surge/sea level rise (blue shading) over average local high tide level (not accounting for local flood defence infrastructure)
Source: Climate Central.

Airports and air transport

As with ports, airports are facilities which include multiple infrastructure components: roadway-type infrastructures (runways, taxiways, access roads, etc.), buildings (terminals, repair warehouses, control towers) and outdoor navigation aids, control and communication equipment. These sub-components are exposed to similar hazards and vulnerabilities as for other transport networks. In addition, airports and air services display some unique vulnerabilities as outlined in (Eurocontrol, 2013). More extreme precipitation and winds can lead to reduced airport capacity and outright interruptions of flight services in some cases. Insofar as extreme precipitation and storm events are expected to become more frequent, these will have knock-on impacts on air travel and delays. Localised changes in wind patterns and convective weather may also impact flight operations and lead to a loss of capacity and delays. Baglin (2012) summarises possible climate change impacts to airport infrastructures as follows:

- Temperature and precipitation changes will have the same impacts to airport pavements and earthworks as in roadway infrastructures. Further, increased salt and chemical usage for de-icing as a result of more frequent low temperatures will have a further negative impact on airport pavements.

- Sea level rise could result in inundation of coastal airports (Figure 2.22).
- Extreme weather phenomena such as storm surges and strong winds may damage outdoor airport equipment and buildings.

Costs of extreme weather: Big (and uncertain) numbers

The previous sections outline the multiple hazards that are linked to extreme weather and to climate change. The direct impacts on infrastructure are but one part of the overall costs that extreme weather imposes on society: users and operators suffer losses of income and material damages to vehicles and cargo and society pays for extreme weather-related crashes in the form of medical care costs and reduced labour inputs.

The direct economic costs associated with the impact of climate change and extreme weather on land-based transportation systems relate to the monetary cost of repairing or rebuilding damaged infrastructure. Analysis of direct disaster costs on a global scale has shown that the annual direct losses from significant natural catastrophes increased by at least an order of magnitude from the 1950s to the 1990s, with these costs inflated by another factor of two when damage from lesser weather events are included (Auld et al., 2006). In the Australian context, a review of natural catastrophes between 1980 and 2008 showed that for the decade 1999 to 2008 insured losses were approximately USD 7 billion, almost doubling the losses recorded for the previous two decades (MunichRe, 2009). Climate change has been identified as a contributing factor to increasing event costs, along with population growth, urbanisation of vulnerable regions, the concentration of population and assets, improved living standards, vulnerability of modern technology systems and societies reliance on uninterrupted service, increased insurance, and global networking (e.g. tourism) (Auld et al, 2006; MunichRe, 2010). The greatest public costs have been found to be related to disaster assistance, and road maintenance, relocation and repair (Middlemann, 2007).

Aside from the direct costs related to infrastructure damages, substantial indirect costs are likely to be experienced because of network effects including costs due to delays, losses from toll roads, freight supply interruption, detours and trip cancellations (Middlemann, 2007; Garnaut, 2008; Koetse and Rietveld, 2009).

Schweikert et al. (2014) estimates climate change adaptation costs for roads and the counterfactual in 10 countries based on the use of a software decision support tool – the Infrastructure Support Planning System (ISPS). This tool investigates infrastructure-linked adaptation costs across a number of areas, including planning, environment, service continuity and social impacts. ISPS evaluates the costs of climate change on two levels. The first based on a proactive "adapt" approach which seeks to make road systems more resilient to climate change by adapting changes in design and construction standards. The second approach, a more reactive "no-adapt" strategy looks solely at the damage and maintenance costs implied by no change in design standards. The approach embedded in the ISPS adopts several performance metrics namely incurred fiscal expenditures, opportunity costs for those expenditures and a "regret" metric. The latter evaluates the amount of money that could be lost if the adopted strategy (adapt vs. no-adapt) is not warranted. It is the potential cost of "over-protection" in the case of the "adapt" strategy and the cost of "under-protection" in the case of the "no-adapt" strategy.

Table 2.8. **Summary of yearly adaptation costs and associated metrics for 10 selected countries in the 2050s**

	Avg. Annual cost Adapt **USD million**		**Avg. Annual cost** No-adapt **USD million**		**Opportunity cost** Adapt		**Opportunity cost** No-adapt		Adapt **"regret"** **USD million**		No-adapt **"regret"** **USD million**	
	Median	Max.	Median	Max.	Median	Max.	Median	Max.	Median	Max.	Median	Max.
Bolivia	6.6	8.4	16.1	56.4	38%	96%	45%	165%	115.7	449.0	298.4	1083.5
Cameroun	3.0	5.7	5.6	15.7	21%	31%	23%	51%	50.6	116.2	168.8	378.8
Croatia	2.3	12.2	2.2	27.3	2%	12%	1%	12%	12.7	78.2	48.1	450.2
Ethiopia	5.0	6.6	16.3	50.9	27%	40%	39%	117%	85.9	227.7	409.2	1220.3
Italy	106.1	153.4	175.4	534.2	8%	11%	9%	16%	1016.6	1524.6	5100.0	9648.1
Japan	122.5	435.6	276.4	1062.6	4%	12%	5%	15%	1168.4	3530.9	6418.5	21020.4
New Zealand	5.8	10.1	8.9	17.2	3%	4%	3%	4%	105.2	193.1	268.9	400.9
Philippines	29.1	32.1	33.9	128.5	44%	48%	56%	88%	340.0	390.8	1715.9	2718.1
Sweden	31.3	103.8	34.5	121.1	6%	13%	6%	14%	1170.6	2603.6	1299.7	2897.0
Venezuela	17.0	20.3	59.4	78.2	16%	19%	25%	33%	192.6	255.9	1219.6	1633.8

Source: Schweikert et al., 2014.

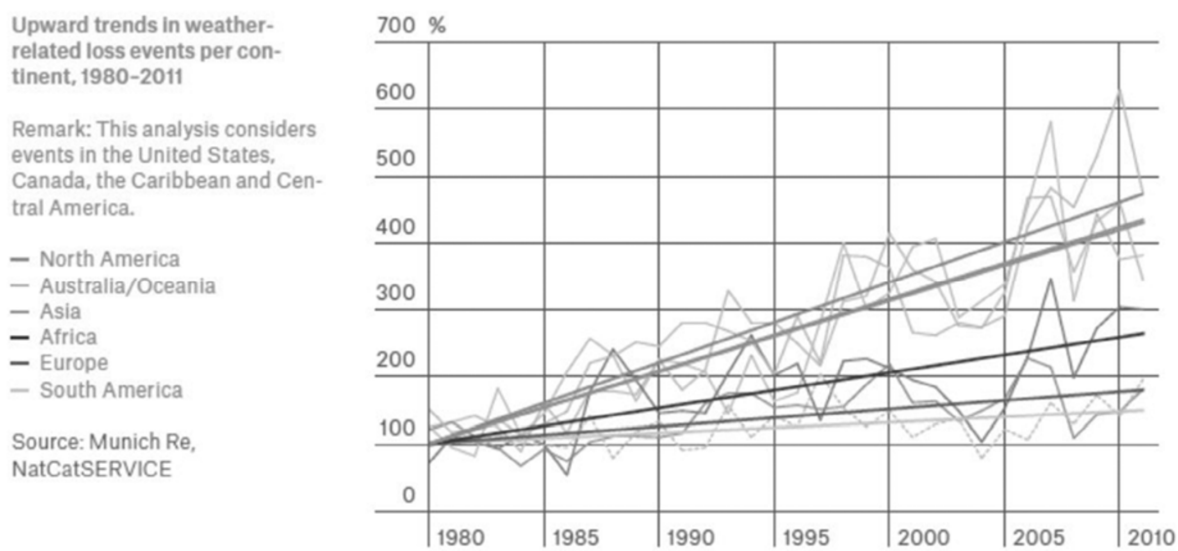
The results outlined in Table 2.8 highlight that proactive adaptation approaches always deliver greater benefits than reactive no-adapt strategies, albeit the benefits (and regrets) vary across regions and levels of economic development. For low income countries (that also display low shares of paved, all-season roads) annual average costs in the 2050s are relatively low (given the lower value of the existing and new road stock) but these represent very high opportunity costs. These findings indicate that for the median ISPS results Bolivia could nearly double its road stock, and Cameroun, Ethiopia and the Philippines could considerably expand their road stock by the 2050s, even with proactive adaptation strategies and minimal or no climate impacts. Higher income countries display higher average annual costs by the 2050s in both the proactive and reactive cases due to extensive all-season paved road networks (and higher construction and maintenance costs). Opportunity costs for these countries are markedly lower in both proactive and reactive cases and the difference between each case is generally lower than for developing countries.

In terms of adaptation or no-adaptation "regret" – that is the amount a country might overspend if taking a proactive approach in the absence of climate change or, conversely, the monetised damage that might occur if a country takes no action other than maintenance and climate change impacts do manifest themselves – the findings in Schweikert et al. (2014) are clear. For both the median and maximum impact range and across all countries studied, a reactive no-adapt approach entails greater regret and costs than a proactive adapt approach. The spread between regret and no-regret outcomes differs greatly across countries however. In Sweden the range is quite narrow – USD 2.6 billion vs. USD 2.9 billion in the median case, whereas in Cameroun those figures are USD 50.6 and USD 168.8, respectively. These findings suggest that while all countries benefit from pro-active adaptation strategies, some countries clearly benefit more.

Nokkala et al. (2012) estimates that the European Union's 27 member states face EUR 15 billion in extreme weather-related costs. This cautious estimate is about 0.1% of the EU-27 GDP, and about EUR 30 annual extra cost to each EU-27 citizen in 2010. These figures were estimated by the Extreme

Weather impacts on European Networks of Transport (EWENT) project and they represented minimum conservative estimates. Whether these costs are significantly on the rise can only be speculated, but the general consensus among researchers is that societies should be prepared for an increase on the basis of this report's current understanding of climate science.

Figure 2.23. **Upward trends in extreme weather occurrences with loss-resulting consequences**



Source: MunichRe, 2012.

Furthermore, only recently have extreme weather costs drawn the attention of project financiers, insurers and their clients. The awareness of these costs has generated both business prospects and managerial challenges. For example, large first and re-insurers have identified new potential private and institutional customers, who want to hedge against extreme weather hazards. MunichRe (2012) has identified clear increasing trends in all types of meteorological and climatological events as well as in the losses these have entailed (Figure 2.23).

While the costs and consequences of extreme weather have been studied on an aggregate level, the tools for internalising the adverse effects and risks are by and large still missing. This internalisation is crucial especially in decisions on new transport system investments. However, climate risk is not the only issue assessed in investment appraisal. Some countries already widely internalise different external effects and risks, such as environmental impacts (noise, emissions and other items) (Maibach et al., 2008), but still in many countries even basic appraisal methods are lacking in investment decisions. Therefore the inclusion of extreme weather risks may be a novel element in many investment appraisal processes.

The costs and benefits of climate change have often been assessed on an aggregate level with varying estimates of both input parameters and selected future scenarios. This leads to a vision of the world where future benefits and costs as well as states-of-the-world can differ significantly from each other. Generally, the analysis and guidance received by policy makers is dominated by macro-level and general analysis of climate change impacts, as has been the case for the Stern Review (HM Treasury, 2012; for others, e.g. de Bruin et al., 2009; World Bank, 2012; HM Government, 2011)

Two recent EU projects assessed the impacts of climate change and extreme weather conditions on transport systems: EWENT and WEATHER. The WEATHER project aimed at identifying risks, economic impacts, and suitable crises management and transport adaptation strategies for all modes of transport across Europe. The EWENT project looked more deeply into long-term weather scenarios and the sensitivities of transport modes by following a standard risk assessment process.[9]

The WEATHER project considered the following extreme events: hot and cold spells, floods, landslides, wild fires and storms. Data were gathered through studies of various weather phenomena on transport in North America, Australia, Europe and New Zealand, a review of damage reports from six countries and an assessment of available transport operator data for some European transport networks. For the assessment period 1998 to 2010, the total costs borne by the transport sector (damages, repair and maintenance costs of infrastructures, vehicle damages, increased system operation costs, etc.) across all weather phenomena were estimated at EUR 2.5 billion per year. The indirect costs of transport disruptions on other sectors were estimated at EUR 1 billion per year. Projections for 2040–2050 (based on predictions of extremes taken from the EWENT project) suggest that rail will face the highest cost increase, with particular emphasis on the British Islands, central Europe and Scandinavia, mostly due to increases in hydrological extremes (Sanchez et al., 2012).

The EWENT project assessed average annual costs due to weather extremes for the current (1998–2010) and a future (2041–2070) time period. Costs comprised accident costs, time costs, infrastructure damage and maintenance, and effects on freight and logistics. EWENT estimated costs from extreme weather events in the baseline period of more than EUR 15 billion, which was dominated by the costs of road accidents (Table 2.9). This estimate was more than four times above the estimates of direct and indirect costs from the WEATHER project (Table 2.10). The main reasons for this difference were a wider definition of extreme events in EWENT, inclusion of externalities (accidents), and the explicit consideration of non-motorised travel and logistics among other aspects, which were omitted by the WEATHER project.

Table 2.9. **EWENT project's estimates on current extreme weather costs for the EU-27 transport system**

Mode	Present costs due to extreme weather, including all phenomena (ca. 2010)				
	Accidents	Time costs	Infrastructure		Freight & logistics
			Physical infra	Maintenance	
Road	**>10 bill. €/a,** mostly borne by the society	**0.5–1.0 bill. €/a,** mostly borne by road commuters	**ca. 1 bill. €/a,** mostly borne by infrastructure managers, ultimately by the taxpayers	**ca. 0.2 bill. €/a,** mostly borne by public infrastructure managers and hence ultimately by the taxpayers	**1–6 bill. €/a,** mostly borne by the shippers
Rail	**>0.1 bill. €/a,** mostly borne by the society	**>10 mill. €/a,** borne by the commuters	**>0.1 bill. €/a,** mostly borne by rail infrastructure managers (=taxpayers)		**5–24 mill. €/a,** borne by the shippers
IWT	**ca. 2 mill. €/a,** mostly borne by society	na	na	na	**0.1–0.3 mill. €/a,** borne by the shippers
Short sea	**>10 mill. €/a,** mostly borne by society	na	na	na	**0.2–1 mill. €/a,** borne by the shippers
Aviation	na	**>0.7 bill. €/a**	na	na	**0.5–2.3 mill. €/a,** borne by the shippers
Light traffic (Mühlhausen 2011)	**>2 bill. €/a,** borne by the society and insurers	–	na	na	–
TOTAL	*>12 bill. €/a*	*>1.2 bill. €/a*	*ca. 1 bill. €/a*	*>0.3 bill. €/a*	*1–6 bill.€/a*
The EU-27 grand total for all modes and all cost items is at present more than 15 bill. euros p.a.					

Source: Nokkala et al., 2012.

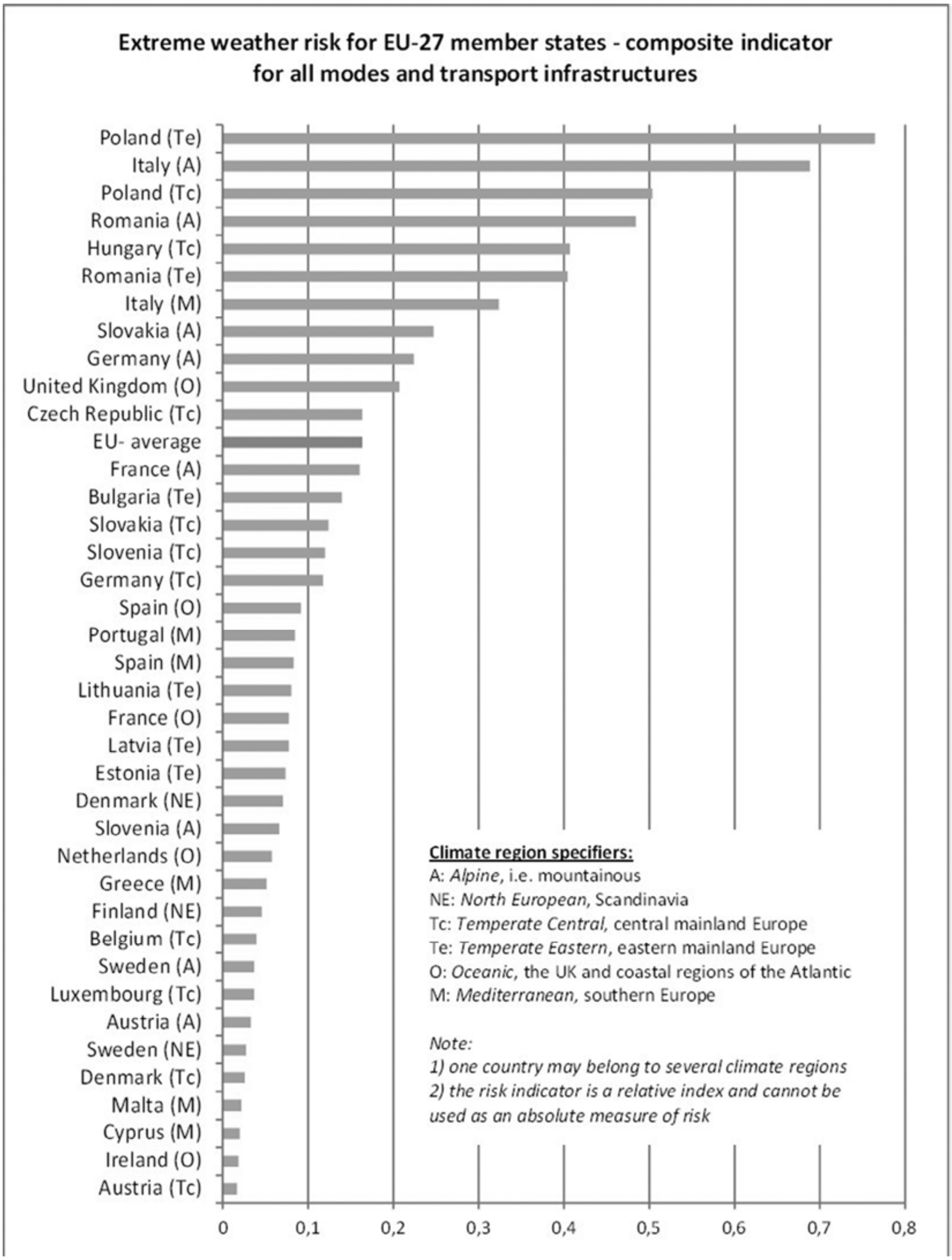
Table 2.10. **WEATHER project's estimates on current extreme weather costs inside the EU**

Extreme weather event		Infrastructure Assets (m€)	Infrastructure Operations (m€)	Vehicle Assets (m€)	Vehicle Operations (m€)	User Time (m€)	Health & Life (m€)	Total (m€)
Storm	Road (1)	76,10	22,60	5,10	1,40	63,00	5,90	174,10
	Rail (2)	0,07		12,05		6,28		18,39
	Maritime (5)			2,10	17,98			20,08
	Intermodal (6) (7)	0,53					0,72	1,25
	Air (8)			53,80	34,30	38,40	28,30	154,80
Winter	Road (1)	248,80	126,30	81,30	12,50	125,50	164,90	759,30
	Rail (2) (3)	0,04		3,38		1,60		5,02
	Intermodal (6) (7)	0,21					0,21	0,42
	Air (8)		11,20	12,00	57,70	64,60	1,90	147,40
Flood	Road (1)	630,10	21,90	24,40	30,01	93,70	21,50	821,61
	IWW (4)					4,87		4,87
	Rail (2)	103,66		111,60		67,30		282,55
	Air (8)			3,20	26,50	29,60	0,20	59,50
	Intermodal (6) (7)	0,32					0,10	0,42
Heat&drought	Road (1)						46,90	46,90
Total		1059,82	182,00	308,92	180,39	494,84	270,63	2496,60

Notes: (1) Average year 2000-2010, (2) Average annual data 1999-2010, (3) Avalanches, winter storms and extreme heat events not included, (4) Average annual data 2003-2009, service providers' costs, (5) Average data hurricane Kyrill 2007 from case studies, freight transport, (6) Average data 2009 freight transport without AT, CH, I, CZ, DE (already included in rail), (7) Including extreme temperatures (heat), (8) Average annual data.

Source: Przyluski et al., 2011.

Figure 2.24. **Relative extreme weather indicators for EU-27**



Source: Compiled from Leviäkangaset al., 2012.

According to the results from EWENT, different regions in Europe will respond to future changes in different ways, because the impacting weather phenomena and their future trends are different (Leviäkangas et al., 2011; Vajda et al., 2011). Furthermore, the aggregate statistics on transport systems and economic contexts combined with climatological data suggest that the risks in different EU member states deviate substantially from each other (Figure 2.24). Typically risks are concentrated to countries, regions and/or areas where:

- transport volume densities are high, which *de facto* means major urban centres and their surroundings as well as main transport corridors
- infrastructures are in poor technical condition and economic resources scarce to respond to/recover from extreme weather events
- weather phenomena can occur in their extreme form and can result in major economic losses.

As the risks are higher in some countries than in others, so will be the costs most likely; special focus is warranted in high-risk countries, regions and areas.

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Notes

1 Or climate-related variables in the case of sea level rise.

2 Scouring refers to the removal of sediment from around *bridge abutments* or piers which are the result of moving water; this process may compromise the structural integrity of a bridge.

3 The following section draws on Youman (2007); Willway et al. (2008); Meyer et al. (2014); Nemry and Demirel (2012).

4 For a description of RCP scenarios, see Chapter 1.

5 Quantity of water in the soil.

6 Forces keeping a collection of particles (for example soil, sand or gravel) together.

7 Such as the "Rational method" (Meyer et al., 2014; Kalantari, 2011) or "Critical storm duration".

8 Rail segments welded together into a single rail of a length of several kilometres.

9 It is noteworthy that the definition of extremes strongly varied between approaches. In both projects it had to be acknowledged that there is a lack of reliable statistical data for a sound cost assessment. For more information, see EWENT (http://ewent.vtt.fi/) and WEATHER (http://www.weather-project.eu/weather/index.php).