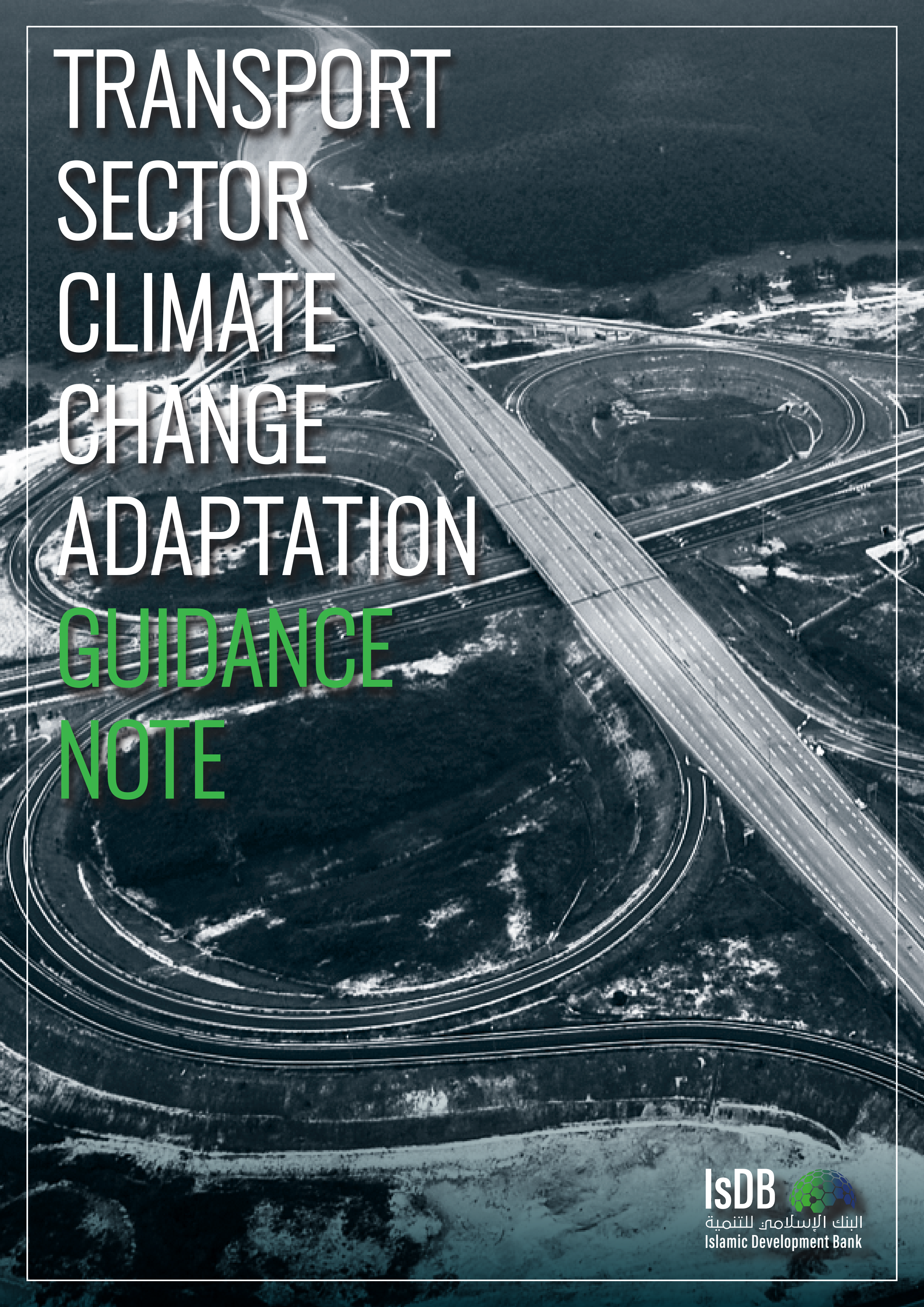
TRANSPORT SECTOR CLIMATE CHANGE ADAPTATION GUIDANCE NOTE



IsDB
البنك الإسلامي للتنمية
Islamic Development Bank

Acknowledgments

The preparation of the transport sector guidance note was led by the Islamic Development Bank (IsDB) Climate Change Division with input from transport sector experts at the IsDB and partner institutions.

The guidance note was developed by the IsDB Climate Change Division (Dr. Ahmed Al Qabany, Olatunji Yusuf) under the general oversight of Dr. Mansur Muhtar, Vice President (Country Programs) and May Babiker, Acting Director, Resilience and Social Development Department.

The guidance note was reviewed and received input from Mohammed Al Sayed (Manager, Economic Infrastructure Division, IsDB), Dr. Daouda Ben Oumar Ndiaye (Climate Change Division, IsDB), Armin Wagner (GIZ) and Levent Toprak (GIZ).

The main author of this guidance note was the World Resources Institute (WRI), technical consultant to the Islamic Development Bank. Special thanks to Lauren Sidner (WRI) and Michael Westphal (WRI) for their efforts in this work.

Disclaimer

1. About this Guidance Note

This transport sector guidance note was prepared by the World Resources Institute (WRI) for the Islamic Development Bank (IsDB) to enable IsDB project teams to integrate information on climate risks into project design. It applies to transport sector projects involving physical assets. The subsectors covered include the following:

- Roadway projects
- Railway projects
- Port projects
- Urban mass transit projects

After a brief background on projected climate changes in the regions where IsDB operates and projected impacts on the transport sector (Section 2), Section 3 explains the purpose of this note within a broader climate risk management process. It describes the steps involved in managing a project's climate change risks—beginning with climate risk screening, followed by project impact and adaptation assessments, and ending with project implementation. Section 4 then describes the process of determining potential climate impacts on transport sector projects and identifying adaptation options to address those impacts. Section 5 presents an approach to evaluate adaptation options, and Section 6 concludes with case studies that demonstrate practical examples of this approach.

2. Background: Climate Change and the Transport Sector

In 2017, IsDB's Ordinary Capital Resources net approvals totaled US$3.9 billion (IsDB 2017). IsDB approved seven transport-related projects for a total of $774.5 million in 2017 (IsDB 2017). Of this total, 82 percent supported roadway projects; the remaining 18 percent supported port projects. Railway projects also constitute an important part of IsDB's transport portfolio (IsDB 2017). IsDB operates in four core regions: the Middle East and North Africa, sub-Saharan Africa, Europe and Central Asia, and Asia and Latin America.[1]

Observed and projected climate changes vary across these regions. Throughout much of Africa, temperatures have increased by at least 0.5°C over the last 50 to 100 years, with minimum temperatures rising faster than maximum temperatures. Much of the region lacks sufficient data to draw conclusions about trends in annual precipitation. However, in the western and eastern Sahel regions, annual precipitation has likely decreased, and in parts of eastern and southern Africa, it has likely increased. In terms of model projections, it is likely that land temperatures over Africa will rise faster than the global average, particularly in the more arid regions. There is considerable uncertainty regarding projected precipitation patterns in sub-Saharan Africa, but there is greater model agreement that precipitation will increase in eastern Africa and decrease in northern and southwest Africa. Across the continent, climate change is expected to exacerbate existing water stress (Niang et al. 2015).

In the past century, much of Asia has experienced warming trends and increasing temperature extremes. There is little agreement on projected precipitation patterns at a subregional scale, but under a higher warming scenario (Representative Concentration Pathway [RCP] 8.5), precipitation is likely to increase at higher latitudes by the middle of the 21st century and in parts of eastern and southern Asia by the late 21st century. Water scarcity is expected to be a major challenge for most of Asia due to increased water demand and poor water management (Hijioka et al. 2014). In Europe, future climate projections vary regionally, with projected temperature increases throughout the region, precipitation increases in northern Europe, and precipitation decreases in southern Europe. Across the continent, climate projections indicate a marked increase in heat waves, droughts, and heavy precipitation events (Kovats et al. 2014).

Lastly, significant trends in precipitation and temperature have been observed in Central and South America, but the patterns vary regionally, with increasing trends in annual rainfall in southeastern South America, decreasing trends in Central America and central-southern Chile. Increased warming has been observed throughout the region, with the exception of the Chilean coast. Increases in temperature extremes have been measured in Central America and most of tropical and subtropical South America, while more frequent extreme rainfall in southeastern South America has produced more landslides and flash floods. Under the RCP 8.5, climate models project a mean reduction of 10 percent in annual precipitation for Central America (with a reduction in summer precipitation) by 2100, a decrease of 10 percent for tropical South America east of the Andes, and an increase of 15 to 20 percent for southeastern South America.

Climate change will impact transport in myriad ways, depending on the mode and location-specific characteristics. There is high confidence that coastal systems and infrastructure in low-lying areas will increasingly experience adverse impacts, including submergence, coastal flooding and erosion due to relative sea-level rise. The Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment report estimated that the mean sea-level rise would increase anywhere from 0.44 meters (RCP 2.6) to 0.74 meters (RCP 8.5) by 2100. Factors including subsidence, sedimentation, and local development will influence localized effects of sea-level rise. While climate change may not alter the frequency of tropical cyclones, it will likely lead to an increase in the most intense tropical storms, further jeopardizing many coastal assets, including transport infrastructure (Wong et al. 2014).

All transportation infrastructure is constructed under design standards that consider very specific temperature and precipitation ranges and return intervals for extreme events, such as floods and extreme heat. Transport infrastructure malfunctions if weather conditions diverge from the design range, which could occur more frequently as the climate continues to change. For example, paved roads and railways are particularly vulnerable to extreme temperatures, while unpaved roads, bridges, and culverts are sensitive to precipitation extremes. In colder regions, the more frequent or higher amplitude freeze-thaw cycles or the melting of permafrost could compromise the structural integrity or roads, rails, and bridges (Arent et al. 2014).

There are also indirect effects of climate change that could impact transportation. Natural disasters and heat waves could lead to mass transit service disruptions, changes in passenger demand, reduced passenger health and comfort, or higher operating costs (e.g., cooling costs or peak electricity pricing). Heat waves are likely to occur with a higher frequency and longer duration in the future (IPCC 2014a). For example, in North Africa, temperatures considered exceptional today will become a new normal under a high-emissions (4°C) scenario (Hallegatte et al. 2016). This will have a profound impact on the ability to design transport networks that are not only climate-proofed from a design perspective, but also able to foster broader climate resilience for the community.

3. Project Climate Risk Management

This guidance aims to help project teams incorporate climate change considerations into project planning and design. It will support the broader climate risk management process, which begins with climate risk screening and concludes with project implementation. Figure 1 below briefly summarizes the climate risk management process.[2] Though the terminology and precise sequencing of steps vary, many comparable institutions, including multilateral development banks and bilateral development agencies, apply processes similar to the one described in Figure 1.

The first phase of the process is climate risk screening. IsDB plans to begin using Acclimatise Aware, a climate risk screening tool, for this phase.[3] It will use Aware at the early concept stage for all projects involving physical assets. In addition to generating an overall climate risk ranking, Aware identifies key climate risk areas for the project, based on project category and location. If the initial climate risk screening using Aware indicates that a project has some level of climate risk, project impact and adaptation assessments follow. This guidance note is meant to support those phases of the climate risk management process.

Climate risk screening and project impact assessment together establish the climate change vulnerability context of a project. That context informs the adaptation assessment that follows, which aims to identify those measures best suited to reduce climate vulnerability, thereby establishing a direct link between specific project activities and the overall objective of reducing climate vulnerability. The sections that follow discuss project impact and adaptation assessments in greater detail.


ΜΑΡΙΑ Α. ΑΓΓΕΛΙΚΟΥΣΗ
ΠΕΙΡΑΙΕΥΣ
IMO 9233703

FIGURE 1: CLIMATE RISK MANAGEMENT PROCESS

CLIMATE RISK SCREENING

Preliminary, rapid assessment of the risks posed to a planned project as a result of climate change. Tools and methodologies used include Acclimatise, Aware; World Bank, Climate and Disaster Risk Screening Tool; International Institute for Sustainable Development, Community-Based Risk Screening Tool—Adaptation & Livelihoods (CRiSTAL).

PROJECT IMPACT ASSESSMENT

- Identify the climatic variables of interest for the project. These may include meteorological (e.g., temperature, precipitation); hydrologic (e.g., runoff volume, groundwater recharge, soil moisture); and other environmental (e.g., sea-level rise) variables. When their impacts are harmful, these variables are referred to as climate hazards.

ADAPTATION ASSESSMENT

- Establish adaptation objective.
- Identify adaptation options.
- Use a multi-criteria approach to appraise adaptation options (e.g., functional effectiveness, technical feasibility, affordability, stakeholder acceptability, etc.).

IMPLEMENTATION

- Establish implementation arrangements for selected adaptation measures (determine roles and responsibilities; identify needs for technical support and capacity building, etc.).

Sources: ADB 2014b; ADB 2013; USAID 2015c; GIZ 2014

• Identify the changes in environmental conditions (or *system impacts*) likely to follow from changes in the above variables (e.g., reduced raw water quality, increased evapotranspiration, increased frequency of floods).	• Determine the vulnerability of different project components to changes in environmental conditions. Vulnerability is a function of th project's exposure, sensitivity, and adaptive capacity to a specific climate hazard.	
• Conduct economic assessment of shortlisted adaptation options.	• Select adaptation strategy.	• Stakeholder engagement is critical to all of these steps.
• Provide for ongoing monitoring and evaluation.		

This guidance note can help to inform these steps.

4. Identifying Potential Impacts and Adaptation Options

As explained above, the Aware climate risk screening tool identifies the key climate risk areas based on the project's type and location. Project teams can use this information, along with other available climate data and expert judgment, to determine which climate hazards are most likely to be relevant for a project. The World Bank's Climate Change Knowledge Portal[4] and The Nature Conservancy's Climate Wizard[5] are two examples of publicly available tools for identifying location-specific climate information (USAID 2017). From there, project teams can begin to evaluate the likely impacts and potential adaptation responses. This section provides tools to support this evaluation.

Identifying Potential Impacts

The decision trees below can guide project teams in identifying potential climate vulnerabilities of roadway projects (Figure 2), railway projects (Figure 3), port projects (Figure 4), and urban mass transit projects (Figure 5). For example, if the Aware tool flags rising temperatures as a key risk area for a proposed road project, the project team would see that increasingly frequent heat waves could cause premature deterioration of asphalt through softening and traffic-related rutting, which could disrupt traffic and increase maintenance costs (see Figure 2).

However, project teams must be aware of several important caveats in using the decision trees. First, the trees provide a generalized overview of potential impacts, but climate change is likely to affect different types of projects across different regions in diverse and highly context-specific ways. Second, the different climate drivers cannot be viewed in isolation. Instead, project teams must consider how the various drivers interact with each other. Some climate drivers may amplify one another, while others counteract one another. At the same time, a variety of nonclimate factors, including population growth, land-use change, economic development, and urbanization, could pose significant challenges to the transport sector (USAID 2014). In many instances, these nonclimate stressors interact with climate stressors in similarly complex ways (USAID 2014).

Third, the decision trees focus primarily on the potential physical impacts of climate change, but climate change could affect the transport sector in diverse ways, including direct and indirect physical impacts and a variety of nonphysical impacts. Potential nonphysical impacts include social and equity-related impacts, as well as market, legal, and reputational impacts. Climate change could induce changes in trading patterns—by causing geographic shifts in agricultural production, for example—that could affect port and freight rail traffic. Climate change could cause shifts in demand or changes in regulatory requirements, but because these nonphysical impacts tend to be context- and project-specific, they are not the focus below. The precise legal impacts, for example, will depend entirely on the legal and regulatory framework in the project country or the specific contractual arrangements underlying a project. That said, upon identifying potential physical project vulnerabilities, project teams should consider whether such vulnerabilities could have follow-on, nonphysical consequences for a particular project.

FIGURE 2: DECISION TREE FOR ROADWAY PROJECTS (pag

CLIMATE HAZARD

Increasing frequency and magnitude of storms

Rising sea levels and increased storm surge heights

SYSTEM IMPACTS

Strong winds associated with more intense storms

Rising relative sea levels and altwater intrusion

PROJECT VULNERABILITIES

Possible wind damage to roadway infrastructure; service disruption if winds leave trees or other debris on roads

Exposure to salinity can deteriorate / corrode roadway surfaces and base layers, culverts, or metal bridge components

Erosion of unpaved roads or road bases may cause road failure or reduce road stability

Increased risk of land-/mudslides, which can damage roads and ma ke them temporarily impassable

ADAPTATION OPTIONS

- ✓Construct strategic wind breaks
- ✓Design roadside infrastructure and bridges to withstand higher wind speeds
- ✓Improve weather forecasting capacity and implement early warning systems
- ✓Implement system to proactively manage roadside vegetation and debris

- ✓Employ corrosion-resistant materials, where feasible
- ✓Relocate or elevate critical equipment
- ✓Treat with protective coatings to slow corrosion
- ✓Construct new or enhance existing coastal protections (levees, seawalls, dikes); enhance nature-based protections, including coastal wetlands and mangroves

- ✓Implement erosion control measures
- ✓Pave unpaved roads where cost-effective
- ✓Use pavement materials that are less susceptible to erosion
- ✓For wave-induced erosion, build new or enhance existing breakwaters and sea walls
- ✓Reroute sections of coastal road exposed to wave action
- ✓Design new bridges to withstand stronger wave action

- ✓Stabilize slopes using physical support structures (e.g., retaining walls) and vegetative reinforcement
- ✓Cut back steep slopes to shallower angle
- ✓Improve slope and subgrade drainage
- ✓Introduce hydraulic binding agents into earthwork material
- ✓Increase monitoring of slopes, subgrade material, and related drainage systems
- ✓Avoid high-risk areas in siting new infrastructure
- ✓Construct green infrastructure near roads to reduce runoff

ge 1)

Increasing precipitation or frequency of extreme precipitation events

Stronger wave action and increased coastal erosion

Increased runoff and erosion

Increased flood risk

Damage to bridge structures; increased scour and erosion of bridge foundations

Increased weather-related traffic accidents; traffic disruption and congestion

Inability to access or safely use roads (esp. unpaved roads) until flooding subsides and related cleanup and repairs are completed

Drainage works overwhelmed; damage to tunnels and underpasses

Deterioration of pavement and road foundations, increasing repair costs and decreasing service life of infrastructure

- ✓Raise bridge decks to accommodate increase in flood volumes
- ✓Reinforce bridge piers and abutments and strengthen foundations (e.g., deepen bridge footings)
- ✓Stabilize stream banks (by installing revetments, gabions, riprap or by increasing vegetation) to prevent erosion
- ✓Construct retention dams upstream to reduce flood flows
- ✓Conduct more frequent inspection and maintenance

- ✓Consider projected flood risk in siting new roadway infrastructure; relocate existing infrastructure away from high-risk areas
- ✓Avoid disruption to regional hydrology and wetlands, which can increase flood risk, in siting new roads
- ✓Raise road surface level to reduce flood damage and ensure continued access during flood events
- ✓Consider flood risk in design/capacity of drain and stormwater systems for new infrastructure
- ✓Upgrade existing road drainage systems to accommodate greater flows; increase culvert capacity
- ✓Increase pumping capacity to evacuate water from tunnels; deploy mobile pumps during intense rains
- ✓Ensure positive cross-slopes to help with water evacuation
- ✓Upgrade unpaved roads (if cost-effective)
- ✓Increase flood protections near roadways; use green infrastructure and retention basins to divert runoff/increase infiltration
- ✓Regular inspection and maintenance of drainage systems
- ✓Improve weather forecasting, develop and implement emergency management plans and early warning systems
- ✓Reduce travel speeds in extreme weather

- ✓Use pavement materials that are better sealed and less susceptible to moisture
- ✓Increase base strength (thickness and/or quality) to increase protection of subgrade layers
- ✓Alter selection of subgrade materials to withstand higher moisture contents; Use hydraulic binding agents in road foundation
- ✓Conduct more frequent maintenance; seal cracked and distressed areas

FIGURE 2: DECISION TREE FOR ROADWAY PROJECTS (pag

CLIMATE HAZARD

Temperature increase

SYSTEM IMPACTS

Warmer winter temperatures

Increase in very hot days and heat waves

PROJECT VULNERABILITIES

Reduced snow and ice removal costs, longer construction, and improved mobility/ safety in some regions

Increased freeze-thaw cycles in some places could create frost heaves and potholes on road and bridge surfaces, disrupting traffic and increasing maintenance costs

Premature deterioration of asphalt through softening and traffic-related rutting may disrupt traffic and increase maintenance cost

ADAPTATION OPTIONS

✓Use more durable pavement materials, including more heat-tolerant asphalt binders and rut-resistant asphalt
✓Use pavement materials/ asphalt mixtures that can tolerate greater variability in temperature
✓Use lighter color pavement materials to decrease heat absorption
✓Increase roadside vegetation and trees to increase shade and decrease exposure to heat
✓Conduct more frequent maintenance; seal cracked and distressed areas and mill out ruts
✓Implement proactive traffic management plans to reduce risk of rutting

✓Replace bridge expansion joints; ensure joints can adequately accommodate thermal expansion
✓Use more durable materials for bridge deck, including reinforced concrete
✓Conduct more frequent inspections and maintenance

ge 2)

Decreasing precipitation and drought

Increased risk of wildfires

Reduced soil moisture

Thermal expansion of bridge joints and degradation of bridge structural materials, causing potential traffic disruptions and increased maintenance cost

Health and safety risks to maintenance / construction workers may limit road work and increase the cost of maintenance

Damage to roadway infrastructure or road closure due to safety risk and reduced visibility

Reduced pavement integrity and possible cracking due to ground shrinking, subsidence

- ✓Alter working hours/seasons to protect workers from extreme heat
- ✓Increase shading by planting trees or constructing shade structures
- ✓Increase crew size to allow for more frequent recovery breaks
- ✓Develop contingency plans to protect passenger and worker safety in extreme heat
- ✓Limit width of roads to what is needed in the longer term to limit heat-island effect

- ✓Develop and implement fuel reduction strategies; identify and remove vegetation that may pose a fire hazard in or near right-of-way
- ✓Development fire breaks near roadways
- ✓Avoid new developments in high-risk areas

- ✓Evaluate risk of drought-related subsidence (projected water availability, soil type, etc.) in siting new infrastructure
- ✓Implement proactive traffic management plans to reduce risk of cracking
- ✓Conduct more frequent inspections and maintenance

FIGURE 3: DECISION TREE FOR RAILWAY PROJECTS (page

CLIMATE HAZARD

Increasing frequency and magnitude of storms

Rising sea levels and increased storm surge heights

SYSTEM IMPACTS

Strong winds or lightning associated with more intense storms

Rising relative sea levels and saltwater intrusion

PROJECT VULNERABILITIES

Potential wind damage to railway infrastructure; service disruption if winds leave trees or other storm debris on tracks

Exposure to salinity, salt spray can increase corrosion of tracks, electrical equipment, and metal bridge components

Increased erosion of track subgrade can wash away ballast and reduce track stability, increasing maintenance costs and potentially requiring speed restrictions

Increased risk of land-/ mudslides, which can damage tracks and make them temporarily impassable

ADAPTATION OPTIONS

- ✓Construct strategic wind breaks
- ✓Design rail-side infrastructure and overhead lines to withstand higher wind speeds
- ✓Improve weather forecasting capacity a nd implement early warning systems
- ✓Implement system to proactively manage track-side vegetation and debris

- ✓Enhance coastal protections (e.g., sea walls, levees)
- ✓Employ corrosion-resistant materials, where feasible
- ✓Relocate or elevate critical equipment
- ✓Treat with protective coatings to slow corrosion

- ✓Stabilize slopes using physical support structures (e.g., various types of retaining walls) and vegetative reinforcement
- ✓Cut back steep slopes to a safer, shallower angle
- ✓Improve slope and subgrade drainage
- ✓Introduce hydraulic binding agents into earthwork material
- ✓Increase monitoring of slopes, subgrade material, and related drainage systems
- ✓Avoid areas with high risk of slides in siting new railway infrastructure
- ✓Introduce hydraulic binding agents into earthwork material
- ✓Implement erosion control measures
- ✓Construct green infrastructure near rail tracks to reduce runoff
- ✓For wave-induced erosion, build new or enhance existing breakwaters and sea walls
- ✓Develop and implement improved methods of detecting subgrade erosion

e 1)

Increasing precipitation or frequency of extreme precipitation events

Stronger wave action and increased coastal erosion

Increased runoff and erosion

Increased flood risk

Damage to electrical equipment and power outages may cause track circuit failures and other operational disruption, including to signaling systems, disrupting service

Flood damage to underground transit systems, including subway stops, trains and tunnels, may disrupt transit service

Flood damage to rail stations, rolling stock, and maintenance facilities

Temporary loss of service until flooding subsides and related cleanup and repairs are completed

✓Elevate and protect signaling and other electrical equipment
✓Deploy mobile power supply substations to be used in case of power outages
✓Increase redundancy in electrical systems
✓Develop contingency plans for electricity disruption

✓Install and maintain emergency pumping capacity to evacuate water from underground transit systems and tunnels; enhance pumping capacity; deploy mobile pumps during intense rains
✓Couple increased pumping capacity with passive rainwater evacuation and management systems
✓Increase flood protections around and/or elevate transit stop entrances
✓Use mobile barriers to prevent water from entering tunnels and underground transit systems
✓Raise sidewalk level ventilation grates so that water doesn't enter underground systems from flooded sidewalks
✓Develop emergency management plans, including passenger evacuation plans for underground systems
✓Upgrade transit tunnel lining to prevent groundwater infiltration

✓Integrate projected flood risk into site assessments for new railway infrastructure
✓Relocate existing infrastructure away from high-risk areas
✓Elevate railway infrastructure, including tracks, rail stations, and electrical equipment
✓Incorporate flood risk into design of stormwater management and drainage systems; retrofit existing systems to deal with increased runoff
✓Conduct frequent maintenance of drainage infrastructure
✓Enhance flood protections near railway infrastructure
✓Increase water retention capacity; use green infrastructure to divert run-off/increase infiltration
✓Install flood-proofing measures (e.g., barriers, gates, shutters)
✓Improve weather forecasting capacity and implement early warning systems
✓Provide temporary alternative transit option

FIGURE 3: DECISION TREE FOR RAILWAY PROJECTS (page

CLIMATE HAZARD

Temperature increase

SYSTEM IMPACTS

Warmer winter temperatures

Increase in very hot days and heat waves

PROJECT VULNERABILITIES

Reduced snow and ice removal costs, longer construction, and improved mobility/ safety in some regions

Increased freeze-thaw cycles or thermal expansion of rail track may cause buckling, and increase safety risks, travel delays, and maintenance costs

Potential for electrical signaling and communications systems to overheat and malfunction

Overhead lines may expand and sag, requiring lines to be shut down and potentially disrupting service

ADAPTATION OPTIONS

✓Replace track elements and rail with more heat-resistant materials
✓Install (additional) expansion joints in frequently buckled sections of rail
✓Impose speed restrictions to ensure safety
✓Consider restricting train loads in extreme high temperatures to avoid buckling
✓Monitor rail track condition and conduct frequent maintenance
✓Paint track white to absorb less heat
✓Increase shading to reduce heat exposure
✓Develop and implement improved methods to detect buckling

✓Increase ventilation and cooling substations, signal rooms, and electrical boxes
✓Replace existing electrical equipment with equipment that can withstand higher temperatures
✓Conduct regular monitoring and maintenance of electrical equipment
✓Install overhead lines with higher design temperature range
✓Install technology to automatically adjust line tension with temperature variation
✓Provide temporary alternative transit option (bus)

e 2)

Decreasing precipitation and drought

Increased risk of wildfires

Reduced soil moisture

Health and safety risks to passengers, transit operators, and maintenance personnel

Increased energy usage and cost for cooling and/or refrigeration; AC units on trains may fail in extreme heat

Thermal expansion of bridge joints, increasing safety risks, travel disruption, and maintenance costs

Damage to railway infrastructure or service disruptions due to safety risk or reduced visibility

Soil shrinkage may cause earthworks failure and uneven rail settlement

- ✓Design trains and transit stops to improve thermal comfort (use heat-resistant materials, tinted windows, windows that open, white painted roofs, etc.)
- ✓Maximize natural ventilation and improve cooling systems in trains and transit stops
- ✓Alter working hours to protect workers from extreme heat
- ✓Increase shading by planting trees or constructing shade structures
- ✓Increase crew size to allow for more frequent recovery breaks
- ✓Make greater use of climate-controlled facilities for loading and unloading rail cars
- ✓Develop contingency plans to protect passenger and worker safety in extreme heat

- ✓Improve energy efficiency to reduce air conditioning costs
- ✓Explore less energy-intensive refrigeration systems for freight
- ✓Upgrade air conditioning on railcars to ensure operability at high temperatures; conduct frequent maintenance

- ✓Replace bridge expansion joints
- ✓Use more durable materials for bridge deck, including reinforced concrete
- ✓Conduct more frequent inspections and maintenance

- ✓Develop and implement fuel-reduction strategies; identify and remove vegetation that may pose a fire hazard in or near rail right-of-way
- ✓Develop fire breaks near rail infrastructure
- ✓Avoid new developments in high-risk areas

- ✓Consider projected water stress in siting new infrastructure; relocate existing infrastructure away from high-risk areas
- ✓Conduct more frequent inspections and maintenance
- ✓Use alternative rail bed material

FIGURE 4: DECISION TREE FOR PORT PROJECTS (page 1)

CLIMATE HAZARD

Increasing frequency and magnitude of storms

Rising sea levels and increased storm surge heights

SYSTEM IMPACTS

Strong winds associated with more intense storms

Rising relative sea levels and saltwater intrusion

PROJECT VULNERABILITIES

Potential damage unreinforced warehouses and cranes; toppled shipping containers

Difficulty berthing ships and inability to operate cranes in high winds may cause congestion and shipping delays

Operational and navigational challenges as sea-level-rise changes relative height of ships

Potential seawater ingress of drainage pipe outlet, impeding drainage and increasing flood risk

Deeper water in navigation channels may allow larger draft vessels to berth or reduce dredging requirements

ADAPTATION OPTIONS

✓Reinforce port buildings and warehouses to withstand higher winds
✓Construct wind breaks
✓Reduce stacking height of containers
✓Select materials handling equipment that can withstand storms
✓Increase storage capacity of existing facilities to account for weather-related delays
✓Improve weather forecasting capacity and implement early warning systems

✓Consider projected sea-level rise in designing new infrastructure or upgrading existing infrastructure, including assessing impacts of sea-level rise on goods handling, navigation, and berthing
✓Elevate docks and wharves and retrofit other facilities to provide adequate clearance
✓Increase the frequency of bridge openings and/or raise the clearance of new bridges
✓Select berthing and goods handling equipment that can accommodate projected rise in sea levels

✓Install valves to drainage outlets to reduce seawater ingress
✓Raise height of drainage outlets

Increasing precipitation or frequency of extreme precipitation events

Stronger wave action and increased coastal erosion

Increased runoff and erosion

Increased flood risk

Increased underscouring of pier foundations, breakwaters, and sea walls and deterioration of port infrastructure

More rapid siltation decreases channel depth and increases dredging requirements

Disruption to goods handling and damage to stored goods may cause shipping delays, reputational damage, or contract liability

Potential damage to and inability to access rail and truck yard infrastructure may disrupt freight supply chain

Potential damage to port buildings/ equipment or to stored goods, increasing maintenance costs

- ✓Raise and reinforce port infrastructure (bridges, decking, revetments, etc.) to withstand stronger wave action
- ✓Build new or enhance existing breakwaters and sea walls
- ✓Create offshore berms or barrier islands; protect and enhance marsh, mangrove, or other intertidal habitats
- ✓Implement erosion control measures (e.g., groynes, beach nourishment)

- ✓Increase dredging of silt/sediment
- ✓Reduce sediment runoff into watercourse using sediment traps, buffer strips, etc.

- ✓Incorporate projected flood risk into site assessment for new port facilities and into design of stormwater management systems
- ✓Increase drainage and pumping capacity
- ✓Construct new or enhance existing coastal protections (e.g., levees, seawalls, dikes)
- ✓Elevate or relocate critical assets and equipment (e.g., backup generators, pump houses, access roads, etc.)
- ✓Raise and fortify bridges, decking, jetties, revetments, dams, spillways, superstructure, etc.
- ✓Install flood-proofing measures (barriers, gates, shutters, etc.) to port buildings and warehouses
- ✓Elevate storage areas or reorganize storage so that perishable cargo is stored in less vulnerable areas
- ✓Enhance nature-based protections like coastal wetlands
- ✓Use green infrastructure to increase water retention and divert runoff
- ✓Improve weather forecasting capacity and implement early warning systems

FIGURE 4: DECISION TREE FOR PORT PROJECTS (page 2)

CLIMATE HAZARD

Temperature increase

SYSTEM IMPACTS

Warmer winter temperatures

Increase in very hot days and heat waves

PROJECT VULNERABILITIES

Improved operating conditions in some regions; opportunities for new ports where navigation is currently restricted by ice

Paved surfaces may deteriorate more quickly, causing potential operational disruptions and increased maintenance cost

Increased stress on temperature-sensitive structures and equipment, including metal warehouses and cranes

ADAPTATION OPTIONS

✓Use more durable pavement materials, including more heat-tolerant asphalt binders and rut-resistant asphalt
✓Use lighter color pavement materials to reduce heat absorption
✓Design new metal structures and equipment to withstand higher temperatures
✓Increase shading to reduce heat exposure
✓Conduct more frequent maintenance

✓Improve energy efficiency of cooling systems and explore less energy-intensive alternatives for refrigerated storage

Decreasing precipitation and drought

Increased surface evaporation decreases lake levels and river flows

Reduced snowpack and spring runoff decrease lake levels and river flows

Reduced water availability

Increased energy costs for air conditioning and refrigeration

Health and safety risks to port operators and maintenance personnel

For ports on lakes and rivers: decreasing water levels may impact navigability and increase dredging requirements

Less water available for port operations

- ✓Alter working hours/seasons to protect workers from extreme heat
- ✓Increase shading by planting trees or constructing shade structures
- ✓Increase crew size to allow for more frequent recovery breaks
- ✓Make greater use of climate-controlled facilities

- ✓Consider projected water availability in siting new port facilities; relocate existing port facilities
- ✓Impose cargo restrictions
- ✓Redesign vessels to accommodate lower water levels
- ✓Increase dredging

- ✓Improve water-use efficiency
- ✓Develop alternative water supplies (e.g., harvesting stormwater) and improve water treatment and recycling

FIGURE 5: DECISION TREE FOR URBAN MASS TRANSIT PR

CLIMATE HAZARD

Increasing frequency and magnitude of storms

SYSTEM IMPACTS

Strong winds or lightning associated with more intense storms

Stronger wave action and increased coastal erosion

PROJECT VULNERABILITIES

Potential service disruption if winds leave trees or other storm debris on tracks or roads

Reduced stability of tracks or road bases due to erosion may require speed restrictions, which increase travel times, or temporary suspension of service

Potential safety risk and temporary loss of service if land-/mudslides damage tracks or roads or make them temporarily impassable

ADAPTATION OPTIONS

✓Construct strategic wind breaks
✓Design rail- or roadside infrastructure and overhead lines to withstand higher wind speeds
✓Improve weather forecasting capacity and implement early warning systems
✓Implement system to proactively manage vegetation and debris near right-of-way

✓Avoid high-risk areas in routing new transit service; reroute existing bus service away from high-risk areas
✓Consider a wide range of transit options (e.g., water taxis and ferries, nonmotorized modes, ride-hailing systems, and connectivity through informal modes, etc.) to create redundancy and provide temporary alternative transit options during service disruption
✓Implement erosion control measures
✓Construct green infrastructure near right-of-way to reduce runoff
✓For wave-induced erosion, build new or enhance existing breakwaters and sea walls
✓Develop and implement improved methods of detecting subgrade erosion
✓Stabilize slopes using physical support structures (e.g., various types of retaining walls) and vegetative reinforcement
✓Cut back steep slopes to a safer, shallower angle
✓Improve slope and subgrade drainage
✓Introduce hydraulic binding agents into earthwork material
✓Increase monitoring of slopes, subgrade material, and related drainage systems
✓Introduce hydraulic binding agents into earthwork material

ROJECTS (page 1)

Rising sea levels and increased storm surge heights

Increasing precipitation or frequency of extreme precipitation events

Increased runoff and erosion

Increased flood risk

Damage to electrical equipment and power outages may disrupt service

Flood damage to underground transit systems, including subway stops, trains, and tunnels, may disrupt transit service

Increased weather-related traffic accidents; traffic disruption, and congestion

Damage to rail stations, bus stops, rolling stock, buses, bus storage lots, and maintenance facilities

Temporary loss of service and/or inability to access transit until flooding subsides and related cleanup and repairs are completed

✓Elevate and protect signaling and other electrical equipment
✓Deploy mobile power supply substations to be used in case of power outages
✓Increase redundancy in electrical systems
✓Develop contingency plans for electricity disruption
✓Consider a wide range of transit options to create redundancy and provide temporary alternative transit options during service disruption

✓Install and maintain emergency pumping capacity to evacuate water from underground transit systems and tunnels; enhance p umping capacity; deploy mobile pumps during intense rains
✓Couple increased pumping capacity with passive rainwater evacuation and management systems
✓Increase flood protections around and/or elevate transit stop entrances
✓Use mobile barriers to prevent water from entering tunnels and underground transit systems
✓Raise sidewalk-level ventilation grates so that water doesn't enter underground systems from flooded sidewalks
✓Develop emergency management plans, including passenger evacuation plans for underground systems
✓Upgrade transit tunnel lining to prevent groundwater infiltration

✓Consider projected flood risk in routing new transit service and in siting associated facilities, including storage and maintenance facilities and transit stops; reroute existing bus service to avoid high-risk areas; relocate existing facilities away from high-risk areas
✓Incorporate flood risk into design of stormwater management and drainage systems; retrofit existing systems to deal with increased runoff
✓Install flood-proofing measures (e.g., barriers, gates, shutters) at transit stations and enhance flood protections near right-of-way and around associated facilities
✓Elevate road and railway infrastructure
✓Increase water-retention capacity; use green infrastructure to divert runoff/increase infiltration Ensure safe, paved last-mile access to transit stations, including by nonmotorized modes
✓Consider a wide range of transit options to create redundancy and provide temporary alternative transit options during service disruption
✓Improve weather forecasting capacity and implement early warning systems
✓Conduct frequent maintenance of drainage infrastructure

FIGURE 5: DECISION TREE FOR URBAN MASS TRANSIT PR

CLIMATE HAZARD

Temperature increase

SYSTEM IMPACTS

Warmer winter temperatures

Increase in very hot days and heat waves

PROJECT VULNERABILITIES

Potential for service disruption and increased safety risks if increase in freeze-thaw cycles or thermal expansion causes damage to roadways or rail

Heat-related deterioration of bus tires or overheating of engines could affect vehicle availability and disrupt scheduled service

Potential for temporary suspension of electric rail service if signaling and communications systems overheat or if overhead lines expand and sag

ADAPTATION OPTIONS

✓Impose speed and load restrictions to ensure safety
✓Consider a wide range of transit options (e.g., water taxis and ferries, nonmotorized modes, ride-hailing systems, and connectivity through informal modes, etc.) to create redundancy and provide temporary alternative transit options during service disruption
✓Use more heat-resistant materials
✓Install (additional) expansion joints in frequently buckled sections of rail
✓Use lighter colored pavement materials or paint tracks white
✓Monitor rail track or road condition and conduct frequent maintenance
✓Increase shading to reduce heat exposure
✓Develop and implement improved methods to detect buckling

✓Design new buses to withstand higher temperatures
✓Use heat-resistant materials, where feasible
✓Upgrade to more efficient and durable engine cooling systems

✓Increase ventilation and cooling substations, signal rooms, and electrical boxes
✓Replace existing electrical equipment with equipment that can withstand higher temperatures
✓Conduct regular monitoring and maintenance of electrical equipment
✓Install overhead lines with higher design temperature range
✓Install technology to automatically adjust line tension with temperature variation
✓Consider a wide range of transit options to create redundancy and provide temporary alternative transit options during service disruption

Sources (Figures 2-5): Quinn, et al. 2017; ADB 2014a; ADB 2014c; ADB 2011; Becker, et al. 2013; ARA 2012; Pulido, et al. 2018; Nemry and Demirel 2012; Fisk 2
Meyer, et al. 2014; OECD 2016; Marteaux 2016; Markolf, et al. 2019; Hodges, et al. 2011; Transportation Research Board 2008; UN Economic Commission for I

ROJECTS (page 2)

Decreasing precipitation and drought

Increased Increased risk of wildfires

Reduced soil moisture

Health and safety risks to passengers, transit operators, and maintenance personnel

Potential shifts in demand to alternative public transit or private transportation

Increased energy usage and cost for cooling and/or refrigeration; AC units on trains and buses may fail in extreme heat

Potential for temporary suspension of bus or train service due to safety risk or reduced visibility

Potential for service disruption if soil shrinkage/ subsidence causes damage to roadways or rail tracks

- ✓Design trains, buses, and transit stops to improve thermal comfort (use heat-resistant materials, tinted windows, windows that open, white painted roofs, etc.)
- ✓Maximize natural ventilation and improve cooling systems in trains, buses, and transit stops
- ✓Alter working hours/seasons to protect workers from extreme heat
- ✓Increase shading by planting trees or constructing shade structures
- ✓Increase crew size to allow for more frequent recovery breaks
- ✓Make greater use of climate-controlled facilities for loading and unloading railcars or vehicle maintenance
- ✓Develop contingency plans to protect passenger and worker safety in extreme heat
- ✓Evaluate potential shifts in demand in planning new transit options; ensure existing transit options can accommodate shifts

- ✓Improve energy efficiency to reduce air conditioning and refrigeration costs
- ✓Explore less energy-intensive refrigeration systems
- ✓Upgrade air conditioning on railcars and buses to ensure operability at high temperatures
- ✓Conduct frequent maintenance

- ✓Develop and implement fuel-reduction strategies; remove vegetation that may pose a fire hazard in or near rail right-of-way
- ✓Reroute bus service
- ✓Development of fire breaks near rail infrastructure
- ✓Avoid new developments in high-risk areas
- ✓Consider a wide range of transit options to create redundancy and provide temporary alternative transit options during service disruption

- ✓Evaluate risk of drought-related subsidence (projected water availability, soil type, etc.) in siting new infrastructure
- ✓Implement proactive traffic management plans to reduce risk of cracking
- ✓Conduct more frequent inspection and maintenance
- ✓Use alternative rail bed material

017; Scott, et al. 2013; International Association of Public Transport 2016; Stipanovic, et al. 2013; Ebinger and Vandycke 2015; Koetse and Rietveld 2012; Europe 2013; USAID 2015a; USAID 2015b; U.S. Climate Change Science Program 2008; EPA 2008; Eichhorst 2009; Eichhorst, et al. 2011; Stenek, et al. 2011.

Identifying Adaptation Options

Once a project team determines potential project vulnerabilities, it can proceed to identify possible adaptation solutions. An important preliminary step is defining the objective of adaptation. In setting objectives, project teams should consider what vulnerabilities they seek to address and what their desired outcomes are. Seeking input from relevant stakeholders for this stage and throughout the process will improve the likelihood that the ultimate adaptation decisions are deemed successful (UK Climate Impacts Programme 2007).

many of the options identified are structural or physical adaptation options. Such options, often referred to as "hard" adaptation options, involve on-the-ground physical infrastructure and technical equipment, like structural flood protections. Structural adaptation options also include a variety of ecosystem- or nature-based adaptation measures (Noble et al. 2014). There are also a variety of nonstructural (or "soft") adaptation options. See Box 1 for more detail on soft adaptation options.

Box 1 | Soft Adaptation Options

"Soft adaptation" encompasses management, operational or policy changes, and capacity-building and knowledge-management activities necessary for successful project implementation. Such measures establish the enabling conditions and institutional design necessary to ensure effective implementation of their "hard adaptation" counterparts. Many soft adaptation measures are not specific to a particular subsector or category of project, and instead, are sensible across a wide range of projects. For example, improved data collection and forecasting capabilities, climate information services, and early warning systems may be critical to the success of projects in any of the subsectors this note covers.

Other examples of soft adaptation measures include **policy measures**, such as modifying design and safety standards for new infrastructure to increase resilience; **capacity-building efforts**, like training or demonstrations on the use of new materials or technologies; and **institutional changes** to support mainstreaming consideration of climate change into development and sector strategies.

Ideally, the objective would include specific timelines and measurable thresholds for what would and would not be considered successful adaptation. For example, the objective could be to achieve a certain level of flood protection (e.g., protect facility from physical damage by 100-year flood event or ensure facility remains fully operational during 50-year flood events) or a certain degree of resilience by a certain date (e.g., ensure facility can resume operations within five days of a 100-year flood event).

Once the team defines its adaptation objectives, it should strive to compile a wide range of measures to meet those objectives. The above decision trees offer an initial, nonexhaustive list of potential adaptation options for addressing particular climate impacts.

Adaptation is context-specific, and the adaptation options identified in the decision trees will not be applicable or appropriate in all cases. For example, some may be too costly, technically infeasible, or socially unacceptable in the project location. The steps described in Section 5 on appraising adaptation options will help project teams determine the appropriateness of different adaptation options for particular projects. Additionally, because this guidance note applies to projects involving physical assets,

Building resilience often requires a combination of hard and soft adaptation measures, as well as engineered and nature-based infrastructure options (GEF-UNEP 2017). As such, in identifying adaptation options, project teams should consider a wide range of options. Consulting with a variety of stakeholders (including community and nongovernmental organizations, environmental specialists, engineers, and others) can help to identify a comprehensive list of adaptation options (ADB 2017b).

When identifying and evaluating adaptation options in the transport sector, it is important to also analyze the mitigation implications of the investments. Globally, the transport sector is responsible for about one-quarter of CO_2 emissions, a 71 percent increase from 1990 (IEA 2018). This does not include the lifecycle emissions of construction materials. Cement alone is responsible for about 8 percent of CO_2 emissions (Olivier et al. 2016), so it is critical to consider the embodied energy and emissions of construction materials used in transport projects (Lehne and Preston 2018), whether they are resilient or not. Moreover, the mitigation and adaptation implications of the broader transport network should be recognized. A well-functioning transport network, with climate-proofed roads, bridges, and associated infrastructure provides community resilience (Hallegatte and Bangalore 2006). However, a climate-proofed transport system need not be low-carbon. A car-dependent road network may be resilient to climate risks yet perpetuate a sprawling urban form that locks in future high emissions. A better alternative is a climate-resilient, low-carbon transport system, focused on transit-oriented development and providing mobility through mass transit and nonmotorized modes.

Finally, in identifying adaptation options, project teams should remember that adaptation measures will ideally be aligned with existing country or sector resilience plans, and that these measures must consider and identify the responsibilities of key actors.

5. Appraising Adaptation Options

A variety of approaches are available for evaluating and prioritizing among adaptation options.[6] One such approach, described below, is to use multi-criteria analysis to identify a short list of preferred adaptation options, followed by a more detailed, quantitative assessment of the remaining options.[7]

At the outset, assessing the performance of different adaptation measures, whether in qualitative or quantitative terms, requires an understanding of future climate conditions. The adaptation options identified in the above decision trees vary widely in cost. The level of investment in adaptation that is economically justified will depend on the severity of potential impacts within the relevant time horizon. Accordingly, project teams must develop climate change scenarios representing plausible future states (ADB 2017b). Project teams first identify the climatic and hydrological variables most relevant to project design. They can then use climate model projections, analysis of historic data, available studies, and expert judgment to develop assumptions about how those variables are likely to change over the project's life span (ADB 2017b). The World Bank's Climate Change Knowledge Portal, mentioned above, includes location-specific climate data and references to a variety of other climate data sources, and the IPCC Data Distribution Centre[8] provides general guidance on the use of scenarios and data in adaptation assessments. Additional analysis, including simulation modeling, may be required to determine how changes in primary climatic and hydrological variables can lead to more complex phenomena, such as drought or flooding (ADB 2017b). Finally, project teams can judge project performance in the context of probable future conditions.

Although climate projections are an imperfect representation of reality, they allow project teams to explore how the future may unfold and how the project will perform under different conditions. That said, uncertainty about future climate conditions creates important methodological challenges for adaptation decision-making, so this section concludes with a brief discussion of the importance of incorporating uncertainty into appraisal of adaptation options.

Multi-Criteria Analysis

Multi-criteria analysis allows for a qualitative and comparative assessment of different adaptation options. It is often used to assess factors that are not easily quantifiable in monetary terms or during preliminary stages when the precise cost implications of various options have yet to be developed (USAID 2015c). Multi-criteria analysis should be conducted in a participatory manner that seeks input from the external stakeholders likely to be affected by the project and by any potential adaptation measures (Morgan et al. 2011).

The project team would first identify the appropriate criteria for the given project. Possible criteria include the following (USAID 2015c; European Commission 2013; Weiland and Troltzsch 2015):

- Functional effectiveness
  - » Does the adaptation measure accomplish the desired outcome?
  - » Does it do so within an acceptable timeframe?
- Technical feasibility
  - » Is the measure technically feasible in the project location?
- Affordability
  - » Are upfront costs of the measure affordable?
  - » Are operations and maintenance costs of the measure affordable?
- Stakeholder acceptability
  - » Does the measure have cultural, economic, or environmental effects that could influence stakeholder or community acceptance?
- Ease of implementation
  - » Are there factors (e.g., those related to human capital, availability of materials, or existing technical skills) that may impede implementation?
- Flexibility/Robustness
  - » How effective will the measure be in the face of uncertain future conditions?
- Sustainability
  - » Does the measure have lasting impact?

» Are the operations and maintenance costs of the measure sustainable?

- Cobenefits

  » Does the measure support other climate-related (e.g., carbon sequestration) or development objectives (e.g., economic security, private sector development, institutional strengthening)?

The project team would then agree on a scale or metric for each criterion. In some cases, quantitative metrics, like cost, may be available. In others, qualitative metrics can be translated into a numerical form (e.g., on a 1 to 5 scale) (USAID 2013; Van Ierland et al. 2013). Project teams could also attach different weights to different criteria to reflect relative importance (USAID 2013).

Next, the project team would score projects incorporating the different adaptation alternatives against each of the criteria. As described above, the performance of different options will depend on projected climate conditions. For example, evaluating the functional effectiveness of a planned shoreline protection measure would require sea-level-rise projections for the lifetime of the project.

Finally, the project team would compare the weight-adjusted scores of the various alternatives (UNFCCC 2011). The project team could use the outcome to produce a short list of preferred options that perform best against the selected criteria.

Detailed Economic Assessment

The remaining options can then be evaluated in greater detail using a quantitative economic assessment. Two possible techniques for economic assessment of adaptation options are cost-benefit analysis and cost-effectiveness analysis (GIZ 2013; UNFCCC 2011).

- *Cost-benefit analysis*

Cost-benefit analysis (CBA) involves quantifying (in present-value terms) and comparing the costs and benefits of an adaptation investment to determine its likely efficiency (UNFCCC 2011). CBA is generally the preferred technique, so long as all costs and benefits of adaptation can be expressed in monetary terms (GIZ 2013). Adaptation costs include direct costs, like initial investment and operating costs, as well as any indirect costs, like transitional costs or social welfare losses (UNFCCC 2011).

Adaptation benefits include benefits accrued and losses avoided as a result of an adaptation measure (IPCC 2007). As such, adaptation benefits are assessed relative to a project baseline (i.e., the project without adaptation).[9] The appropriate project baseline and net benefits of different adaptation options relative to that baseline are ultimately dependent on future climate conditions. Project teams first assess the costs and benefits of the project baseline under projected climate conditions. Where multiple future scenarios are plausible, there would be multiple baselines (European Commission 2013). They then assess the net benefits of various adaptation alternatives relative to the baseline(s).

Adaptation projects often involve impacts on things like public health, environmental quality, or cultural heritage. These sorts of nonmarket costs and benefits are difficult to quantify but should not be excluded from any economic analysis that is conducted. Instead, techniques like contingent valuation should be used to estimate nonmarket costs and benefits, where possible (UNFCCC 2011). Contingent valuation uses the stated preferences of impacted individuals to estimate the economic value of nonmarket goods, like ecosystem services. For example, contingent valuation could be used to estimate the monetary value of an artificial wetland's benefit to water quality by asking impacted individuals how much they would be willing to pay for an equivalent water quality improvement.

Having quantified all costs and benefits, project teams discount them to present value and aggregate them to compute the net present value (NPV) of each alternative. The NPVs of different adaptation options can then be compared to identify the most suitable option or options.

- *Cost-effectiveness analysis*

Cost-effectiveness analysis identifies the least cost option or set of options for achieving adaptation objectives (UNFCCC 2011). It can be applied when adaptation benefits are difficult to quantify and express in monetary terms.[10] Cost-effectiveness analysis may also be appropriate in situations where the issue is not whether to adopt adaptation measures, but rather how to achieve a certain level of adaptation in the most cost-effective way.

Like cost-benefit analysis, this technique requires planners to quantify (in monetary terms) the various costs of adaptation options. Project teams quantify all costs, discount them to present value, and aggregate them. Rather than quantifying project benefits in monetary terms, project teams quantify them in physical terms (Watkiss et al. 2013). The unit of measurement depends on the adaptation objective. Project teams can then compare different options in terms of their cost effectiveness, measured as cost per unit of benefit delivered.

Incorporating Uncertainty into Adaptation Decision-Making

Traditional economic assessment techniques, like those described above, assume an ability to confidently predict future climate conditions or at least attach probabilities to possible future scenarios. In reality, there is considerable uncertainty about the speed, direction, and magnitude of future climate changes in many regions, particularly on the scale relevant to a specific project (Ranger et al. 2013). Uncertainty has countless sources, including uncertainty about emissions trajectory and uncertainty stemming from climate models and efforts to downscale model projections to regional or local levels, particularly in areas with complex topography (ADB 2015). Questions surrounding future socioeconomic development, population growth, and other nonclimate stressors only add to this uncertainty.

The presence of uncertainty does not invalidate techniques like cost-benefit analysis or cost-effectiveness analysis, but decision-makers must take uncertainty into account, and doing so might require them to alter their decision-making approach. Traditional decision-making processes predict future conditions and design projects that perform optimally under those conditions. Alternatively, if multiple future states are possible, probabilities of occurrence can be attached to the different future states, and projects can then be designed to maximize expected NPV. As uncertainty increases, however, this sort of "predict-then-act" approach becomes less applicable (Hallegatte et al. 2012).

Rather than using economic assessments to identify the optimal solution for a single, best-guess projection, decision-making under uncertainty is focused on increasing the robustness of a project—that is, the project's ability to fulfill its intended objective across a range of plausible futures (Hallegatte et al. 2012). Certain simple strategies exist for adding robustness to traditional decision-making processes (Ray and Brown 2015).

- *Incorporating safety margins into adaptation planning* (Hallegatte et al. 2012). Where the marginal cost is low, incorporating safety margins into adaptation planning is a practical way to deal with uncertainty over future conditions. Increasing the height of a planned sea wall to hedge against the worst-case scenario is an example of a safety margin strategy (Ray and Brown 2015). Factors such as incremental cost, consequences of system failure, and life span of the asset would all inform the size of any safety margin incorporated into a project (Ray and Brown 2015). This sort of conservative approach is especially important when the adaptation measure under consideration is irreversible (Hallegatte et al. 2012).
- *Stress testing the outcomes of economic assessments using sensitivity analysis* (Penning-Rowsell et al. 2013). Sensitivity analysis tests how changes in key parameters impact project performance (Ray and Brown 2015; Penning-Rowsell et al. 2013). In particular, project teams can test the sensitivity of the project's NPV to changes in uncertain variables, such as rainfall projections (ADB 2015). While a practical tool for exploring the possible impacts of uncertainty on project performance, sensitivity analysis is subjective, relying on judgment rather than empirical evidence, and as such, is of limited usefulness in the presence of substantial uncertainty (ADB 2015).
- *Identifying no-regret and low-regret measures to implement in the near term that will yield benefits regardless of the nature and extent of climate change.* No-regret and low-regret options are beneficial even if climate projections end up being incorrect (Hallegatte et al. 2012). An example is use of weather forecasting and climate information to improve operational management. One way to identify no- or low-regret strategies is to recognize present problems that can be cost-effectively addressed using measures that also reduce longer-term climate vulnerabilities; in fact, addressing current adaptation deficits is often an effective near-term, no-regrets strategy (Hallegatte et al. 2012).

Decision-making under uncertainty also emphasizes flexibility. Because uncertainty will decrease over time, flexible approaches that can be modified or reversed as more information becomes available are preferable (UNFCCC 2011). This includes both structural and planning flexibility. Structural flexibility involves engineering features so that infrastructure can be enhanced in the future if climate impacts are high. Planning flexibility refers to decision-making that is intentionally iterative and designed to be adjusted over time (UNFCCC 2011).

In situations of greater uncertainty (situations involving investments in long-lived infrastructure, for instance), project teams may need to turn to new, more complex methodologies specifically designed to support decision-making in the context of uncertainty. These include robust decision-making (Lempert et al. 2006; Lempert et al. 2013; Hallegatte et al. 2012; Swart et al. 2013), real options analysis (Swart et al. 2013; Hallegatte et al. 2012; Linquiti and Vonortas 2012), and portfolio analysis (Swart et al. 2013). The details of these methodologies are beyond the scope of this guidance; but briefly, robust decision-making uses sophisticated analytical tools to identify adaptation strategies that perform well over a wide range of possible future climates (Ray and Brown 2015). Real options analysis extends more traditional cost-benefit analysis to explicitly include valuation of the flexibility or adaptability of design options; it can be useful in deciding whether to invest in adaptation immediately or to delay investment (Hallegatte et al. 2012). Portfolio analysis guides the selection of a set of adaptation options (rather than a single option) that together perform well across a range of plausible future climates (Hunt and Watkiss 2013).

6. Case Studies

The following case studies provide illustrative examples of how the above processes might look in practice. The first describes a roadway infrastructure project underway in southwest Bangladesh in a coastal area that is highly susceptible to flooding, tropical cyclones, and sea-level rise. The second describes an urban mass transit project in Peshawar, Pakistan. In particular, it describes efforts to develop the city's first bus rapid transit corridor.

Enhancing the Resilience of Rural Roads in Coastal Bangladesh

The Coastal Climate-Resilient Infrastructure Project is upgrading and climate proofing roadway infrastructure in 12 coastal districts in southwest Bangladesh (ADB 2012b). The project, which was prepared under the Pilot Program for Climate Resilience (PPCR), seeks to improve mobility in agricultural production areas and secure connectivity between these areas and relevant markets. In total, it will upgrade 537 kilometers of rural roads (ADB 2012b).

Vulnerability Assessment

Since the 1960s, average minimum and maximum temperatures in Bangladesh have increased. Climate modeling projects higher average and extreme temperatures; by 2050, temperatures are expected to rise by between 1.9°C and 2.4°C (ADB 2012a). Higher temperatures can cause premature deterioration of roadway infrastructure. In particular, extreme temperatures can cause thermal expansion and rutting of paved surfaces, and bitumen seals may become more susceptible to softening. These impacts could increase maintenance requirements and reduce the overall service life of roadway infrastructure.

Average annual rainfall has also increased since the 1960s. In the future, Bangladesh's rainy summer season will become wetter, while its dry winter season will become dryer. Specifically, monsoon rainfall is projected to increase by as much as 10 percent by 2050, and winter rainfall is projected to decrease by around 5 percent (ADB 2012a).

Between 1977 and 1998, relative sea levels along the coast of Bangladesh rose by between 4.0 and 7.8 millimeters (mm). Estimates of projected sea-level rise vary, but for purposes of project assessments, the project team adopted an estimate of 7 mm per year relative sea-level rise (ADB 2012b). Moreover, Bangladesh already experiences relatively frequent tropical cyclones, and evidence suggests that the number and intensity of tropical cyclones in the Bay of Bengal will increase in the future (ADB 2012a). Together with sea-level rise, more intense storms will bring higher storm surges, stronger wave action, and greater wind speeds.

Bangladesh's low-lying coastal area is already highly susceptible to flooding. An increase in monsoon rainfall, sea-level rise, and more intense storms will exacerbate coastal flood risk. Flooding can make roads inaccessible until floodwaters subside and related repairs and debris-clearing activities are completed. Additionally, flooding can damage road embankments and reduce the structural integrity of road foundations. Finally, heavy rainfall, flooding, and wave action associated with increasingly severe storms can have significant erosive effects on exposed infrastructure, including road embankments and bridge abutments.

Adaptation Measures

The project team sought to address these potential risks in several ways. To address risks associated with rising temperatures, bitumen with a higher softening point will be used for bitumen-surfaced roads (ADB 2012a).

In light of projected flood risks, the project team set a target level for road surfaces based on anticipated monsoon flood level and sea-level rise over the 20-year road design life. Existing standards dictate that roads should be at least 600 mm above the normal annual flood level, but the project team's analysis projected 140 mm of sea-level rise plus 60 mm of subsidence over the 20-year period. As such, the project team added a 200 mm buffer to the standard 600 mm and set the target level for project road surfaces of 800 mm above the normal annual flood level (ADB 2012a).

In addition to elevating roads, the project team sought to ensure that road earthworks would be protected from flood and wave erosion by incorporating additional embankment protection and culverts. Project design will increase cross drainage structures to approximately two per kilometer of road. Embankment protection will mainly involve use of grass turfing and shrubs, but additional geotechnical measures and flood-resistant concrete will be used along key stretches of road where the risk of erosion is high, such as near bridges and large culverts (ADB 2012a).

The project is under implementation and is expected to be completed by June 2019. Once complete, the project team estimates that inundation of the upgraded infrastructure will be reduced by 75 percent, below a 2012 baseline.

Climate Proofing Peshawar's Bus Rapid Transit System

The Peshawar Sustainable Bus Rapid Transit Corridor Project, currently underway in Pakistan, is constructing Peshawar's first sustainable bus rapid transit (BRT) corridor with the aim of improving mobility, reducing travel times and vehicle operating costs, and enhancing local air quality (ADB 2017c). The project, which is funded by the Asian Development Bank (ADB), Agence Française de Développement (AFD), and the European Investment Bank (EIB), will construct a 26 kilometers BRT corridor in dedicated lanes, 31 stations, 2 bus depots, and several park-and-ride facilities. Additionally, it will add bike lanes and improve sidewalks and street lighting all along the BRT corridor (ADB 2017c).

An initial climate risk screening found that the project had medium climate risk. As such, the project team conducted a more in-depth climate risk and vulnerability assessment (CRVA) (ADB 2017a).

Vulnerability Assessment

Temperature

Since 1950, average minimum and maximum temperatures in Peshawar have increased, and climate modeling suggests that these trends will continue. Annual average temperature is predicted to increase by 1.9 to 2.5oC by 2070. Additionally, by 2100, the number of extreme hot days will increase, and heat waves will become more frequent (ADB 2017a).

The BRT road surfaces are mainly bituminous. Rising temperatures increase the risk of traffic-related rutting and softening of paved surfaces along the BRT corridor. Heat can accelerate the deterioration of bitumen seals, making pavement more brittle and susceptible to cracking and potentially allowing water to seep into roadways. These impacts would increase maintenance and repair costs and could potentially result in the premature deterioration of BRT corridor roads.

Additionally, higher temperatures could increase heat-related stress on the vehicles (including engines and tires), as well as energy usage and costs of BRT facilities. Notably missing from the CRVA is any discussion of the potential health and safety impacts of higher temperatures on passengers and personnel.

Precipitation

Total annual precipitation has also increased in Peshawar since 1950, with the most significant increases occurring during monsoon season. Moreover, extreme precipitation has become more frequent over the same time period. In 2010, for instance, Peshawar experienced 274 mm of rainfall in 24 hours, causing severe flooding that impacted over 2.25 million people. Projected future rainfall patterns show high interannual variability. As a result, establishing future trends in local precipitation patterns is difficult. Climate models suggest that annual rainfall may decrease somewhat by 2040, but they fail to establish a clear trend in the future frequency of extreme rainfall events (ADB 2017a).

Although climate modeling does not establish a clear trend for the future frequency of extreme precipitation events, heavy rainfall and flooding are a current threat that should be taken into account. Community consultations and other assessments conducted in connection with the CRVA identified several key points along the route where flood risks are especially high. The route also includes certain features that contribute to the risk: it crosses canals in various places, some of which are significant contributors to urban flooding. It also includes several tunnel or trench sections at junctions.

Extreme precipitation can overwhelm urban stormwater management systems, leading to flooding. Flooding can disrupt BRT service, and damage roads and underground tunnels by increasing soil moisture levels, erosion, and scouring. For instance, heavy rainfall and flooding can increase erosion of road bases, exposed embankment faces, and bridge support structures.

Wind

Projecting future wind patterns is challenging, and climate modeling, in this case, does not establish a clear trend. However, intense wind storms—like a 2015 storm that brought damaging 110 km per hour winds—occasionally affect Peshawar (ADB 2017a). Such events could threaten the stability of signage, lighting, and signaling equipment along the BRT route, without which BRT service could not run safely and smoothly.

Adaptation Options

The CRVA identifies a variety of options for addressing potential project vulnerabilities. To reduce the risk that higher temperatures and heat waves cause more rapid degradation of paved surfaces, the CRVA suggests that the project use materials with greater heat resistance, including stiff bitumen. If continuously reinforced concrete is used, temperature reinforcement should be used to minimize expansion and cracking (ADB 2017a).

The CRVA does not directly address how the project design will manage potential health and safety impacts of higher temperatures on passengers and personnel. However, it does note that the City of Peshawar will have to increase green spaces and cooling areas to offset the growing urban heat island effect (ADB 2017a). Station design also incorporates shade structures, and the CRVA encourages planting trees along the BRT corridor; both of these measures may help improve passenger and personnel comfort.

With regard to heat-related stress on the bus fleet, the CRVA suggests the use of low-air-pressure or tubeless tires. Because higher temperatures could increase energy use in BRT facilities and fleet, the CRVA notes that the project should seek, where possible, to conserve energy along the BRT route and in BRT facilities. For example, it should seek to increase energy efficiency by using energy-saving light bulbs in BRT buildings and in street lighting (ADB 2017a).

Elevating embankments and increasing drainage capacity are critical to addressing project vulnerabilities associated with heavy rain and flooding. Additionally, the CRVA suggests that the project design incorporate green infrastructure, like multifunctional green spaces and bioswales, to increase water retention and infiltration. Permeable pavement for pedestrian paths and bike lanes could also help reduce runoff (ADB 2017a).

In terms of road pavement design, road layers should be well sealed to keep water from infiltrating road bases. Where flood risk is high, continuously reinforced concrete pavement may be better suited to withstand frequent inundation. All tunnel entrances and vent shafts should be elevated, and stations should be designed to ensure stormwater drains quickly and effectively, including through passive drainage and pumping. To increase slope stability and reduce erosion, the CRVA suggests reducing gradients of roadside slopes, constructing masonry retaining walls, and planting trees and vegetation along roadways (ADB 2017a).

The CRVA proposes designing signage, lighting, signaling equipment, and other tall structures, particularly at elevated terminal stations, to withstand wind storms of at least 110 km per hour. To do so, it will strengthen supports and anchorage for these structures, and it will construct strategic windbreaks (ADB 2017a).

Appendix I: Glossary

Adaptation. The process of adjustment to actual or expected climate change and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate change and its effects.

Adaptive capacity. The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.

Climate change. Climate change refers to a change in the state of the climate that can be identified (for example, via statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use.

Exposure. The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Hazard. The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term 'hazard' usually refers to climate-related physical events or trends or their physical impacts.

Impacts. The effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes.

Projection. A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Resilience. The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

Risk. The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard. In this report, the term "risk" is used primarily to refer to the risks of climate-change impacts.

Risk management. Plans, actions, or policies to reduce the likelihood and/or consequences of risks or to respond to consequences.

Sensitivity. The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise).

Uncertainty. A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior.

Vulnerability. The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.[11]

Appendix II: Bibliography

ADB (Asian Development Bank). 2011. Guidelines for Climate Proofing Investment in the Transport Sector: Road Infrastructure Projects. Mandaluyong City, Philippines: ADB.

ADB. 2012a. Climate Change Assessment and Adaptation Strategy. Coastal Climate-Resilient Infrastructure Project. Mandaluyong City, Philippines: ADB.

ADB. 2012b. Report and Recommendation of the President to the Board of Directors. Coastal Climate-Resilient Infrastructure Project. Mandaluyong City, Philippines: ADB.

ADB. 2013. Guidelines for Climate Proofing Investment in the Energy Sector. Mandaluyong City, Philippines: ADB.

ADB. 2014a. Climate Proofing ADB Investment in the Transport Sector: Initial Experience. Mandaluyong City, Philippines: ADB.

ADB. 2014b. Climate Risk Management in ADB Projects. Mandaluyong City, Philippines: ADB.

ADB. 2014c. Technologies to Support Climate Change Adaptation in Developing Asia. Mandaluyong City, Philippines: ADB.

ADB. 2015. Economic Analysis of Climate-Proofing Investment Projects. Mandaluyong City, the Philippines: ADB.

ADB. 2017a. Climate Risk and Vulnerability Assessment. Peshawar Sustainable Bus Rapid Transit Corridor Project. Mandaluyong City, Philippines: ADB.

ADB. 2017b. Guidelines for Climate Proofing Investment in Agriculture, Rural Development and Food Security. Mandaluyong City, Philippines: ADB.

ADB. 2017c. Report and Recommendation of the President to the Board of Directors. Peshawar Sustainable Bus Rapid Transit Corridor Project. Mandaluyong City, Philippines: ADB.

Arent, D.J., R.S.J. Tol, E. Faust, J.P. Hella, S. Kumar, K.M. Strzepek, F.L. Tóth, and D. Yan. 2014. "Key Economic Sectors and Services." In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, et al. Cambridge, UK, and New York: Cambridge University Press, 659–708.

Becker, A., M. Acciaro, R. Asariotis, E. Cretegny, P. Crist, M. Esteban, A. Mather, et al. 2013. "A Note on Climate Change Adaptation for Seaports: A Challenge for Global Ports, a Challenge for Global Society." Climate Change 120 (4): 683–95.

ARA (Australasian Railway Association). 2012. Assessing the Impact on Rail Infrastructure. Climate Change Adaptatiofnemn Position Paper. Canberra: ARA.

Ebinger, Jane Olga, and Nancy Vandycke. 2015. Moving Toward Climate-Resilient Transport: The World Bank's Experience from Building Adaptation into Programs. Washington, DC: World Bank Group.

Eichhorst. Urda, 2009. Adapting Urban Transport to Climate Change. Sustainable Transport: A Sourcebook for Policymakers in Developing Cities, Module 5-F. Bonn, Germany: GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit).

Eichhorst, Urda, Montserrat Miramontes, and Daniel Bongardt. 2011. "Climate-Proof Urban Transport Planning: Opportunities and Challenges in Developing Cities." In Building Resilience to Climate Change in Asian Cities. edited by Konrad Otto-Zimmermann. Bonn: ICLEI.

European Commission, Directorate-General Climate Action. 2011. Guidelines for Project Managers: Making Vulnerable Investments Climate Resilient. https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/non_paper_guidelines_project_managers_en.pdf.

Fisk. Greg. 2017. Climate Risks and Adaptation Pathways for Coastal Transport Infrastructure: Guidelines for Planning and Adaptive Responses. Gold Coast, Australia: National Climate Change Adaptation Research Facility (NCCARF).

GEF-UNEP (Global Environment Facility-United Nations Environment Programme). 2017. Technologies for Climate Change Adaptation: Agricultural Sector. Technology Needs Assessment (TNA) Guidebook Series, UNEP.

GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit), 2013. Economic Approaches for Assessing Climate Change Adaptation Options under Uncertainty. Bonn, Germany: GIZ.

GIZ. 2014. Guidelines for Climate Proofing Water Investments in the MENA Region. Bonn, Germany: GIZ.

Hallegatte, S., and M. Bangalore. 2006. Transport Policies for Climate Change: The Transformative Role Transport Can Play in Mitigation and Adaptation Connections. Washington, DC: World Bank.

Hallegatte, S., M. Bangalore, L. Bonzanigo, M. Fay, T. Kane, U. Narloch, J. Rozenberg, D. Treguer, and A. Vogt-Schilb. 2016. Shock Waves: Managing the Impacts of Climate Change on Poverty. Climate Change and Development Series. Washington, DC: World Bank.

Hallegatte, S., A. Shah, R. Lempert, C. Brown, and S. Gill. 2012. "Investment Decision Making Under Deep Uncertainty—Application to Climate Change." Policy Research Working Paper No. WPS 6193. Washington, DC: World Bank Group.

Hijioka, Y., E. Lin, J.J. Pereira, R.T. Corlett, X. Cui, G.E. Insarov, R.D. Lasco, et al. 2014. "Asia." In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, et al. Cambridge, UK, and New York: Cambridge University Press, 1327–70.

Hodges, Tina, et al. 2011. Flooded Bus Barns and Buckled Rails: Public Transportation and Climate Change Adaptation. Federal Transit Administration (FTA) Report No. 0001. Washington, DC: U.S. Department of Transportation.

Hunt, A., and P. Watkiss. 2013. Portfolio Analysis: Decision Support Methods for Adaptation: Portfolio Analysis. Briefing Note Series: Summary of Methods and Case Study Examples from the MEDIATION Project. Briefing Note 5. https://mediamanager.sei.org/documents/Publications/sei-mediation-briefing5-portfolio-analysis.pdf.

IEA (International Energy Agency). 2018. CO2 Emissions from Fuel Combustion 2018. Paris: IEA.

International Association of Public Transport. 2016. Urban Rail, Climate Change, and Resilience, A joint report by the Metro Committee, the Light Rail Committee, and the Regional and Suburban Railways Committee, Brussels.

IPCC (Intergovernmental Panel on Climate Change). 2014a. Climate Change 2014. Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by R.K. Pachauri and L.A. Meyer. Geneva: IPCC.

IPCC. 2014, "Glossary." In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Annexes. Contribution of Working Group II to the Fifth Assessment Report of the IPCC, edited by J. Agard, J. Birkmann, M. Campos, C. Dubeux, et al. Cambridge University Press, Cambridge, UK, and New York, 1–32.

Islamic Development Bank (IsDB). 2017. Annual Report 2017. Jeddah, Saudi Arabia: IsDB. https://www.isdb.org/sites/default/files/media/documents/2018-12/IsDB-Annual%20Report-1438H%282017%29.pdf.

Koetse, Mark, and Piet Rietveld. 2012. "Adaptation to Climate Change in the Transport Sector." Transport Reviews: A Transnational Transdisciplinary Journal 32 (3): 267–86.

Kovats, R.S., R. Valentini, L.M. Bouwer, E. Georgopoulou, D. Jacob, E. Martin, M. Rounsevell, et al. 2014. "Europe." In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, et al. Cambridge, UK, and New York: Cambridge University Press, 1267–326.

Lehne, J., and F. Preston. 2018. Making Concrete Change: Innovation in Low-Carbon Cement and Concrete. London: Chatham House.

Lempert, R., D. Groves, S. Popper, and S. Bankes. 2006. "A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios," Management Science 52 (4), 514–28.

Lempert, R., N. Kaira, S. Peyraud, Z. Mao, S.B. Tan, D. Cira, and A. Lotsch. 2013. Ensuring Robust Flood Risk Management in Ho Chi Minh City. Policy Research Working Paper No. 6465. Washington, DC: World Bank.

Linquiti, P., and N. Vonortas, 2012. "The Value of Flexibility in Adapting to Climate Change: A Real Options Analysis of Investments in Coastal Defense." Climate Change Economics 3 (2): 125–57.

Markolf, Samuel, Christopher Hoehne, Andrew Fraser, Mikhail Chester, and B. Shane Underwood. 2019. "Transportation Resilience to Climate Change and Extreme Weather Events: Beyond Risk and Robustness." Transport Policy 74: 174–86.

Marteaux. Olivier. 2016. Tomorrow's Railway and Climate Change Adaptation: Executive Report. London: Rail Safety and Standards Board.

Meyer, Michael, Michael Flood, Jake Keller, Justin Lennon, Gary McVoy, Chris Dorney, Parsons Brinckerhoff, et al. 2014. Climate Change, Extreme Weather Events and the Highway System: A Practitioner's Guide and Research Report. National Cooperative Highway Research Program Report 750 Series. Washington, DC: NCHRP.

Nemry, Françoise, and Hande Demirel. 2012. Impacts of Climate Change on Transport: A Focus on Road and Rail Transport Infrastructures. Brussels: European Commission Joint Research Centre.

Niang, I., O.C. Ruppel. M. Abdrabo, and A. Essel, C. Lennard, J. Padgham, and P. Urquhar. 2014. "Africa." In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, et al. Cambridge, UK, and New York: Cambridge University Press, 1199–265.

Noble, I., S. Huq, Y.A. Anokhin, J. Carmin, D. Goudou, F.P. Lansigan, B. Osman-Elasha, et al. 2014. “Adaptation Needs and Options.” In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, et al. Cambridge, UK, and New York: Cambridge University Press.

OECD (Organisation for Economic Co-operation and Development). 2016. Adapting Transport to Climate Change and Extreme Weather: Implications for Infrastructure Owners and Network Managers. International Transport Forum Research Report. Paris: OECD.

Olivier, J., G. Janssens-Maenhout, M. Muntean, and J. Peters. 2016. Trends in Global CO2 Emissions: 2016 Report. The Hague: PBL Netherlands Environmental Assessment Agency. http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-inglobal-CO2-emissions-2016-report-103425.pdf.

Penning-Rowsell, Edmund, N. Haigh, S. Lavery, and L. McFadden. 2013. “A Threatened World City: The Benefits of Protecting London from the Sea,” Natural Hazards 66 (3): 1383–404.

Pulido, Daniel, Georges Bianco Darido, Ramon Munoz-Raskin, and Joanna Charlotte Moody. 2018. The Urban Rail Development Handbook. Washington, DC: World Bank Group.

Quinn, Andrew, A. Jack, S. Hodgkinson, E. Ferranti, J. Beckford, and J. Dora. 2017. Rail Adapt: Adapting the Railway for the Future. Paris: International Union of Railways.

Ranger, N., T. Reeder, and J. Lowe. 2013. “Addressing ‘Deep’ Uncertainty over Long-Term Climate in Major Infrastructure Projects: Four Innovations of the Thames Estuary 2100 Project,” European Journal of Decision Process 1: 233–62.

Ray, Patrick, and Casey Brown. 2015. Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework. Washington, DC: World Bank Group.

Scott, Helen, Darryn McEvoy, Prem Chhetri, Fatima Basic, and Jane Mullett. 2013. Climate Change Adaptation Guidelines for Ports. Enhancing the Resilience of Seaports to a Changing Climate Report Series. Gold Coast, Australia: National Climate Change Adaptation Research Facility (NCCARF).

Stenek, Vladimir, Jean-Christophe Amado, Richenda Connell, Olivia Palin, Stewart Wright, Ben Pope, John Hunter, et al. 2011. Climate Risk and Business: Ports. Washington, DC: International Finance Corporation (IFC).

Stipanovic, Irina, Andreas Hartmann, Herbert ter Maat, and Geert Dewulf. 2013. Risk Assessment of Climate Change Impacts on Railway Infrastructure, Engineering Project Organization Conference Working Paper.

Swart, R. and Singh, T. 2013. MEDIATION and the Adaptation Challenge: Identifying Appropriate Methods and Tools to Support Climate Change Adaptation Decision Making, Final Report of the European Union (EU) MEDIATION Project.

Transportation Research Board. 2008. Potential Impacts of Climate Change on U.S. Transportation. Transportation Research Board Special Report 290. Washington, DC: National Research Council of the National Academies.

UK Climate Impacts Programme, 2007. Identifying Adaptation Options. https://ukcip.ouce.ox.ac.uk/wp-content/PDFs/ID_Adapt_options.pdf.

UNFCCC (United Nations Framework Convention on Climate Change). 2011. Assessing the Costs and Benefits of Adaptation Options: An Overview of Approaches. https://unfccc.int/resource/docs/publications/pub_nwp_costs_benefits_adaptation.pdf.

United Nations Economic Commission for Europe. 2013. Climate Change Impacts and Adaptation for International Transport Networks. New York and Geneva: United Nations.

USAID (United States Agency for International Development). 2013. Analyzing Climate Change Adaptation Options Using Multi-Criteria Analysis. https://www.climatelinks.org/resources/analyzing-climate-change-adaptation-options-using-multi-criteria-analysis.

USAID. 2014. Climate-Resilient Development: A Framework for Understanding and Addressing Climate Change. https://pdf.usaid.gov/pdf_docs/PBAAA245.pdf.

USAID. 2015a. Incorporating Climate Change Adaptation in Infrastructure Planning and Design: A Guide for USAID Project Managers—Bridges. https://www.climatelinks.org/sites/default/files/asset/document/BRIDGES_PRIMER_CCA_ENGINEERING_DESIGN.pdf.

USAID. 2015b. Incorporating Climate Change Adaptation in Infrastructure Planning and Design: A Guide for USAID Project Managers—Roads. https://www.climatelinks.org/sites/default/files/asset/document/ROADS_PRIMER_CCA_ENGINEERING_DESIGN.pdf.

USAID. 2015c. Incorporating Climate Change Adaptation into Infrastructure Planning and Design – Overarching Guide: A Methodology for Practitioners. https://www.climatelinks.org/sites/default/files/asset/document/OVERARCHING_METHODOLOGY_CCA_ENGINEERING_DESIGN.pdf.

USAID. 2017. Primer: Using Climate Information for Climate Risk Management. https://www.climatelinks.org/sites/default/files/asset/document/2017_USAID_Primer-Using-Climate-Info-for-CRM.pdf.

U.S. Climate Change Science Program. 2008. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. Synthesis and Assessment Product 4.7. http://www.iooc.us/wp-content/uploads/2010/09/Impacts-of-Climate-Change-and-Variability-on-Transportation-Systems-and-Infrastructure-Gulf-Coast-Study-Phase-I.pdf.

U.S. Environmental Protection Agency (EPA). 2008. Planning for Climate change Impacts at U.S. Ports. White Paper prepared by ICF International for the US EPA. Washington, DC.

Van Ierland, E.C., K. de Bruin, and P. Watkiss. 2013. Multi-Criteria Analysis: Decision Support Methods for Adaptation, MEDIATION Project. Briefing Note Series: Summary of Methods and Case Study Examples from the MEDIATION Project. Briefing Note 6. https://mediamanager.sei.org/documents/Publications/sei-mediation-briefing6-multi-criteria-analysis.pdf.

Watkiss, P. and Hunt, A. 2013. Method Overview: Decision Support Methods for Adaptation. Briefing Note Series: Summary of Methods and Case Study Examples from the MEDIATION Project. Briefing Note 1. http://www.mediation-project.eu/platform/pbs/pdf/Briefing-Note-1-LR.pdf.

Weiland, Sabine, and Jenny Troltzsch, BASE Evaluation Criteria for Climate Adaptation (BECCA), European Community's Seventh Framework Programme. https://base-adaptation.eu/base-evaluation-criteria-climate-adaptation-becca.

Wong, P.P., I.J. Losada, J.-P. Gattuso, J. Hinkel, A. Khattabi, K.L. McInnes, Y. Saito, and A. Sallenger. 2014. "Coastal Systems and Low-Lying Areas." In Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, et al. Cambridge, UK, and New York: Cambridge University Press, 361–409.

World Association for Waterborne Transport Infrastructure. Climate Change Adaptation: Portfolio of Measures. https://www.pianc.org/climate-change-adaptation-portfolio-of-measures.

Endnotes

1. For additional information on IsDB's operations, see https://www.isdb.org/where-we-work.
2. See Appendix 1 for a glossary of key terms used in Figure 1 and throughout the note.
3. For more information on the Acclimatise Aware tool, see http://www.acclimatise.uk.com/analytics/applications/.
4. For more information on the World Bank Climate Change Knowledge Portal, see http://sdwebx.worldbank.org/climateportal/index.cfm.
5. For more information on The Nature Conservancy's Climate Wizard, see http://www.climatewizard.org/.
6. See, e.g., GIZ (2014), European Commission (2013), and USAID (2015c).
7. The proposed approach draws on European Commission (2013) and USAID (2015c).
8. For more information on the IPCC Data Distribution Centre, see http://www.ipcc-data.org/index.html.
9. ECONADAPT Toolbox: Cost-Benefit Analysis, available at https://econadapt-toolbox.eu/node/12.
10. ECONADAPT Toolbox: Cost-Effectiveness Analysis, available at https://econadapt-toolbox.eu/cost-effectiveness-analysis.
11. All definitions in Appendix 1 taken from IPCC (2014b).