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Database on adaptation measures

Considerations on adaptation pathways in transport sector

Note by the secretariat

I. Background

1. At its twenty-fourth session, the Group of Experts on Assessment of Climate Change Impacts and Adaptation for Inland Transport (GE.3) reviewed and provided comments on the draft guidance on adaption pathways in the transport sector prepared by a group of volunteers who engaged in the intersessional work to elaborate the guidance.

2. In response to comments received, two documents have been prepared for consideration by GE.3. This document, as first of the two documents, provides considerations on adaptation pathways in transport sector.

3. The main author of this document is Dr. S.A. Hashmi, University of Birmingham. Substantive inputs were provided by Dr. E Ferranti and Prof A. Quinn, University of Birmingham, T. Popescu, Directorate General for Infrastructure, Transport and Mobility of France and GE.3's Vice-Chair, C. Evans, PIARC, R. Burbidge, Eurocontrol and L. Wyrowski (United Nations Economic Commission for Europe (ECE) secretariat).

4. GE.3 is invited to review it.

II. Scope

5. Climate change is known to contribute to more frequent and intense weather events, including floods, heatwaves, storms, and other extreme weather phenomena. These events can have significant impacts on transport infrastructure, services, and users. Transport infrastructure owners and operators must adapt to a range of these hazards associated with a changing climate. Adaptation pathways can be described as a sequence of interlinked and flexible actions that can be progressively implemented, based on future dynamics and changes to risk, through early actions that do not compromise future actions and assist in providing overall adaptation to climatic changes. The use of adaptation pathways can assist transport infrastructure owners and operators to adapt their existing assets to maintain desired

operational performance under future and perhaps unknown climate conditions. This guide seeks to provide guidance to transport infrastructure owners, operators and managers on understanding and developing adaptation pathways for their individual transport assets. The guide provides an adaptation pathways framework suited for use by transport infrastructure professionals to structure short- medium- and long-term climate preparedness planning.

III. Considerations on adaptation pathways in transport sector

Context and literature review on adaptation pathways

1. Introduction

6. In the coming decades, global warming and the resulting climate change is anticipated to further increase the frequency, intensity, spatial extent, duration and timing of extreme weather events such as heavy rainfall, potentially causing unprecedented extremes. Over many areas of the globe, the frequency and intensity of heavy precipitation or the proportion of total rainfall from heavy rainfalls is likely to increase with continued warming in the 21st century. Mean sea level rise is expected to contribute towards the increase in extreme coastal high-water levels and projected precipitation and temperature changes imply possible changes in floods [0, 0].

7. Extreme weather events can damage and disrupt transport infrastructures in a multitude of ways. For instance, heavy rainfall events can result in flooding or landslides that cause road and rail closures or increase road congestion and the frequency of accidents. Road closures can also affect the evacuation of areas and can impact the ability for emergency services to access these locations affected. High temperatures can lead to various issues for railway infrastructures, such as failure of electrical equipment or track-buckling, which can further cause service disruptions. Overall, climatic changes such as increasing sea levels and temperatures along with growing intensity and frequency of extreme weather events (such as heavy rainfall and heatwaves) are threatening to compromise European transportation services and transport infrastructure. Such impacts on the transport sector can have destructive consequences and thus, transport infrastructure operators and owners must increase their preparedness by adapting to a range of hazards associated with climate change in order to reduce weather-related service disruption and subsequent financial costs. Future climate scenarios should be considered when installing new assets since transportation infrastructures have a design life of several decades (such as tunnels, tracks and bridges) in order to prevent unstable infrastructure or costly retrofitting. With existing assets and networks, these may need to be adapted to ensure that they are more robust in response to increasing climate hazards in order to continue providing and maintaining service provision and/or to avoid rising costs due to the consequences of extreme weather [0]. On the whole, as part of the climate change adaptation process and inherently improving resilience, transport infrastructure operators and owners must consider an uncertain future climate that may result in unpredictable future socioeconomic situations for crucial transport infrastructure elements such as design, asset repair and management, business operations and continuity, emergency responses, and supply chain management [0]. However, it is expected that with tools such as climate impact and risk assessments as well as stress testing frameworks [0], gaining knowledge and understanding potential impacts of climate change on transport infrastructure will be possible. Through these assessments, infrastructure owners and operators can identify and evaluate the specific climate-related risks and vulnerabilities that their infrastructure may face.

8. Currently, there exists a huge database of various sectoral climate change adaptation planning guides that enable communities to deal with the impacts, risks and opportunities posed by a changing climate. These guidelines intend to assist local communities in formulating local adaptation plans or implementing some steps from it. Such guides provide comprehensive guidance on each step of the adaptation planning process, which includes the major step of identifying and evaluating possible adaptation options. While these are an excellent aid in understanding the significant steps of adaptation planning, especially for non-experts and beginners in the fields of climate change, it appears that the latter stage of

identifying and evaluating possible adaptation options is one that requires a further detailed explanation as it leads to the development of pathways of measures (i.e. exploring a series of options rather than opting for a single ‘once and for all’ solution).

9. Climate change adaptation plans and strategies must consider changes in magnitude or frequency of extreme weather events, long-term climatic changes, and anticipated socioeconomic shifts in population, technology, or governance [0, 0]. It is identified that many adaptation planning approaches can be focused on the cost-benefit analysis of individual local interventions, and may not be suitable for all applications due to the slow-onset nature of climate change events, particularly when combined with complex systems consisting of a mix of extremely long-life assets (for example, bridges) and short-life elements (such as digital systems assets) [0]. Sustainable development revolves arounds the topics of climate change and uncertain future conditions. Based on the complexity and uncertain nature of social-environmental challenges, planning approaches that promote adaptability must accommodate changing conditions over time.

10. Currently, there are several approaches available that are aimed at supporting decision-makers in dealing with uncertainty in long-term decision-making and emphasise the need for adaptability in plans in order to cope with deep uncertainty. Examples of such approaches include:

- Adaptation pathways - offer insights into the sequencing of actions over time, potential lock-ins, and path dependencies [0].
- Adaptive policymaking - offers a step-by-step approach for developing a basic plan, and contingency planning to adapt the basic plan to new information over time [0].
- Scenario planning - a practical technique utilised to inform decision-making under uncertainty, through the exploration of a range of future states and consideration of alternative response options [0].
- Robust decision-making - offers insights into conditions under which issues arise, and makes trade-offs transparent [0].

11. These approaches support choosing near-term actions, while allowing for possibilities to modify, extend or alter plans in response to future changes. Amongst all these approaches, it has been observed several times that the adaptation pathways approach has several benefits: is an analytical approach unlike the adaptive policymaking method that is more of a qualitative approach, does not need much data like robust decision-making, and can be less time-consuming than other methods such as scenario planning that require the use of a high number of scenarios to be robust [0, 0].

2. Adaptation pathways

12. Adaptation pathways can be broadly described as a sequence of interlinked and flexible actions that can be progressively implemented, based on future dynamics and changes to risk, through early actions that do not compromise future actions and assist in providing overall adaptation to climatic changes. These sequence of options combine long-term adaptation plans for a range of climate scenarios with short-term objectives and actions [0, 0, 0, 0]. Therefore, the adaptation pathways approach must be central to the adaptation options generation and analysis. It must be noted that by this point, the earlier stages of setting objectives, reviewing past data and future climate scenarios as well assessing vulnerabilities along with risks using a relevant methodology would be achieved already.

13. The adaptation pathways method offers insights into the sequencing of actions over time, thus considering a large ensemble of transient scenarios for an extensive variety of uncertainties about future developments to be considered in the planning process. The approach includes trends and system changes as well as uncertainty due to natural variabilities. The adaptation pathways approach uses a fast and simple model that enables exploring several pathways over the ensemble, which can then be used to draft adaptation pathways maps [0]. Adaptation pathways mapping is a visual representation that illustrates different potential trajectories or pathways for adapting to climate change over time. It provides a framework for understanding and planning adaptive actions based on different scenarios and future conditions. Elements such as time horizon, scenarios, decision points,

adaptation options, trade-offs and uncertainties, and stakeholder engagement are usually a part of such maps. Adaptation pathways maps can vary, ranging from simple timelines with decision points and options to more complex diagrams illustrating multiple scenarios and interconnected pathways. Therefore, the design for the map should be tailored to the specific context and needs of the adaptation planning process to effectively communicate the range of possible adaptation pathways.

14. Adaptation pathways offer a promising decision-focused approach that incorporates flexibility into decision-making, accounts for future uncertainties, and integrates ongoing monitoring of climate change and its impacts. By incorporating regular monitoring, decision-makers can track the speed and magnitude of climatic changes and assess the effectiveness of implemented adaptation measures. Monitoring provides crucial information on the evolving climate conditions and related impacts, allowing for timely interventions and adjustments to adaptation strategies. This iterative process ensures that adaptation pathways remain responsive to emerging information and enables decision-makers to identify suitable intervention times based on the observed changes in climate and their impacts. By integrating monitoring aspects, adaptation pathways enhance the adaptive capacity of systems and facilitate informed decision-making in the face of evolving climatic conditions. Development of adaptation pathways and their implementation by infrastructure operators and owners can help adapt their current assets and networks to maintain current or improved levels of service and desired operational performance under future climate conditions. In a typical adaptive plan, adaptation pathways capture the implementation process by specifying which measure(s) are to be considered now and which are planned to be implemented once certain conditions (often defined with thresholds for climate variables) are met, or can be confidently predicted to be met in a defined timeframe.

15. The adaptation pathways approach allows for adaptation to take place in stages or phases, where each phase can be planned and designed in a way that reduces the overall risk to an acceptable level as the climate or weather changes. In addition, contrary to a typical project management approach where each phase is planned to occur at a known and specific time, the phases in an adaptation pathways approach can be modified and implemented once the overall risk reaches a pre-determined threshold level [0].

16. With the application of the adaptation pathways approach to adaptation planning, it is possible to create a network or interconnected set of actions that can continue providing sustainable and efficient services as climate hazards develop into the future [0]. To elaborate, once a known action has reached its threshold level, another action can replace it to maintain the delivery of services while reducing any disruptions or physical damage on the infrastructure. These pre-determined threshold levels are usually set based on critical factors such as maintenance inspections, condition monitoring, medium and long-term weather forecasts and decadal climate forecasts and climate projections and they are usually defined through regular risk reassessments [0]. However, a key point to consider is the lead time needed to put actions into operation, in particular to ensure that no safety issues are compromised. Understanding of the lead time allows planners to plan accordingly about how far ahead of a threshold being reached they need to start preparing for introducing another action. Of course, such judgements can be prompted through the use of adequate monitoring systems and the use of climate indicators (such as the frequency of flood events). Therefore, the use and application of an adaptation pathways approach eases the process of identifying the point at which new adaptation actions are required along with assisting in pinpointing when to begin the lead-in process for implementing adaptive actions. Through such a tactic, it is highly likely that by the time actions are initiated, there is an increased confidence on when the threshold level will be reached, allowing for appropriate actions to be implemented. Also, such an adaptation pathway planning approach allows for the adaptation process to evolve at the same pace as the changing climate, without needing to know in advance what that pace or level of change is [0].

17. While the adaptation pathway approach helps improve long-term planning for climate change under future uncertainties, local applications are important to understand the usefulness of the approach to asset owners and planners. From time to time, there may be instances that the hazard levels reach a point where current objectives cannot be accomplished beyond a certain level of climate change. For example, beyond a certain sea

level rise, it might be determined that no further defences are feasible or affordable and thus the continuation of transport services in that particular area are no longer viable. In such cases, applying incremental changes shall be unfeasible and thus, a transformation change is needed, such as rerouting the transport options. At such times of need, prior understanding of threshold levels would prove invaluable as it can assist with planning to avoid further development in vulnerable areas and to develop inexpensive and effective options to meet new objectives [0].

18. Overall, adaptation pathways hold immense promise for building resilience and addressing the impacts of climate change on transport infrastructure and systems. However, it is crucial to acknowledge and address potential challenges associated with this approach. These challenges may include difficulties in determining critical decision points, uncertainties about financial and legal responsibility for decisions and associated impacts, costs, and risk mitigation, and complications with encouraging broader societal commitments and stakeholder engagement. Section 5 of this document delves further into these challenges. Understanding and navigating these challenges will be vital to harnessing the full potential of adaptation pathways and achieving sustainable, climate-resilient outcomes.

3. Summary of commonly used expressions for adaptation pathways

19. A number of academic-practitioner groups have brought a great wealth of knowledge in developing concepts on adaptation pathways. The table provides a list of some commonly used expressions and their relevance in describing and discussing the adaptation pathways approach, based on the views of different groups of researchers and practitioners. It is expected that transport professionals can benefit from these expressions and their explanations to better understand the guidance provided in this paper.

Summary of some commonly used expressions and their relevance in discussing adaptation pathways

Expression	*Explanation*
Adaptation	Adaptation in the context of climate change refers to responses that reduce the negative impacts of a changing climate, while taking advantage of potential new opportunities. This can include making adjustments to economic, social or ecological systems in response to current or anticipated climatic stimuli and their effects [0].
Adaptation measure	A specific action implemented to reduce the impacts of climate change or to increase adaptive capacity [0].
Adaptation option	A mix of measures taken to reduce the impacts of climate change or to increase adaptive capacity [0].
Adaptation pathways	A sequence of interlinked and flexible actions (adaptation options) and decision points that can be progressively implemented over time, to address impacts from climate change, based on future dynamics and changes to risk [0, 0, 0].
Adaptation pathways map	A graphical representation of adaptation pathways.
Adaptive capacity	The ability of systems and institutions to adjust to potential damage, to take advantage of opportunities, or to respond to consequences of impacts of environmental variability and change. It includes adjustments in both behaviour and in resources and technologies [0].
Adaptive design	Climate adaptive design can prepare infrastructure from their design phase for natural disasters. It seeks high and low-tech solutions to environmental and ecological design that can make infrastructures regenerative, resilient, and adaptive to climate change impacts.
Adaptive policies	Policies that address changes over time and make explicit provision for learning [0].

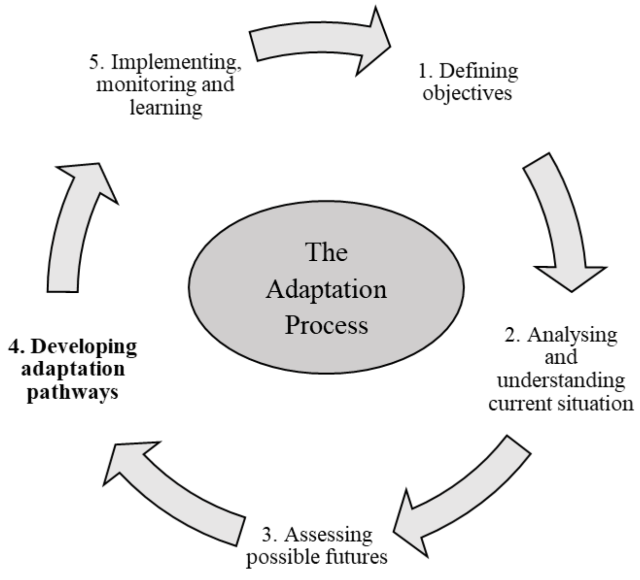
Expression	*Explanation*
Adaptive management	A systematic process for repeatedly enhancing management policies and practices through learning from the outcomes of operational programs [0]. Adaptive management strategies can support planners and managers seeking to overcome the inherent uncertainty surrounding climate change, its impacts and find appropriate responses [0].
Cascading impacts	Impacts arising when extreme weather/climate events occur where an extreme hazard generates a sequence of secondary events in natural and human systems resulting in, natural, social, physical or economic disruptions, where the resulting impact is expressively larger than the initial impact [0].
Climate Indicators / Trigger / Signposts / Thresholds	Often referred to as thresholds, adaptation tipping points, or triggers (see individual definitions), these are embedded within developed pathways to symbolise when an adaptation measure or a management strategy is no longer viable and a different adaptation strategy must be implemented [0, 0].
	Thresholds are points at which a system begins to function in a significantly different way. Thresholds can be physical, environmental, economic or social [0].
	Critical thresholds -Thresholds beyond which a system can begin to fail critically and/or operating the system is unacceptable or untenable.
Deep Uncertainty	Type of uncertainty where stakeholders and decision makers do not know or find it difficult to agree on how likely different future scenarios are [0].
Decision points	Often occurring before a threshold or use-by-date, these are points in time where progress reviews as well as alternate response choices need to be made [0]. At specific points during the adaptation planning process, policymakers and stakeholders evaluate the available information, assess the effectiveness of the measures implemented so far, and consider new data and projections. Decisions on whether to continue with the current approach, adjust it, or select an entirely different pathway are then made.
Interdependencies	Climate change related interdependencies refer to the interconnections between various climate risks (such as increasing temperature and reducing precipitation that will impact the availability and quality of critical resources), which then have an influence on various sectors (such as energy).
	Also, modern urban infrastructure systems are highly interdependent, formed of multiple connections, feedback and feedforward paths, and intricate branching. This indicates that if one system fails, it can result in cascading impacts on other systems (for example, a power failure can possibly have an influence on railway operations) [0].
Levels of risk (acceptable or unacceptable)	Adaptation pathways are designed based on acceptable or unacceptable levels of risk. A pathway switch is needed when the level of risk is no longer considered acceptable, as indicated by the suitable indicators. Usually, stakeholder perspective or an occurrence of extreme weather event determines the acceptable level of risk [0, 0, 0].
Maladaptation	Actions and responses to climate change that may demonstrate short-term adaptation in one key decision-making area but may have detrimental and negative outcomes in other areas or even the same area in the longer-term [0]. Maladaptive decisions or strategies may contribute to the creation or exacerbation of stranded assets.
Multi-criteria analysis (MCA) or Multi-criteria Decision Making Method (MCDM)	An effective and convenient decision-making tool that can address
	an extensive range of sectors, combine costs and benefits along with other qualitative options [0].

Expression	*Explanation*
No-regret, low-regret and win-win options	No-regret actions are usually cost-effective adaptation actions applicable for existing climate conditions and are consistent with addressing climate change risks. These actions have no hard trade-offs with other policy objectives. Low-regret adaptation actions are fairly low-cost and offer comparatively large benefits for predicted future climates. Win-win adaptation actions contribute to adaptation and at the same time they also have other environmental, economic and social benefits [0].
Resilience	For transport assets, resilience refers to the capacity of transportation infrastructure, systems, and networks to withstand and recover from disruptive events, stresses, and changing conditions, while maintaining their functionality and providing essential services to users. [0].
Tipping point	A critical threshold (a level of change in the system) beyond which a system reorganises, often abruptly, and does not return to the initial state (i.e. irreversible changes) even if the drivers of the change are abated [0].
Trigger point	Predetermined thresholds or indicators that act as signals to initiate specific actions or responses in the face of changing climate conditions or impacts. Trigger points help decision-makers recognise when it is necessary to implement adaptation measures or adjust existing strategies to address the evolving risks.
Turning point	Situations where significant changes or shifts occur in the approach to managing climate change impacts. This may be due to changes in climate, social values and interests or policy objectives [0].

4. Prerequisites for the development of adaptation pathways

20. While this guide is intended to provide guidance to transport infrastructure asset owners, operators and managers on developing adaptation pathways, there is a certain expected level of knowledge and understanding that is needed to fully comprehend the guidance and thereafter implement it. Essentially, the development of adaptation pathways is a part of a simple 5-step adaptation planning process, as shown in the figure.

The simplified five steps of any typical adaptation pathways planning process (Adapted from [0]).



21. The first step in the adaptation planning process is to define the objectives, targets and goals as well as including key indicators that can be used to assess success (i.e. whether or not a goal has been reached). This first stage requires the transport infrastructure owners and managers to determine what they want to ultimately achieve and is therefore a crucial initial step as not defining properly or incorrectly setting the objectives can usually have an influence on all the proceeding planning stages, thus impacting the produced adaptation pathways. Thus, objectives should be specific, measurable and time-framed, while relating to an overall goal. Objectives are likely to be revised, changed or even abandoned over time. The framework described in ECE/TRANS/WP.5/GE.3/2023/2 expects that this step or stage is already carried out by the relevant transport infrastructure owners and managers who are interested in developing adaptation pathways for their assets [0].

22. To enable an efficient application of the adaptation pathways framework, objectives should be defined relatively to a level of risk, since the adaptation objective is likely to differ based on the risk level [0]. In the first phase of defining objectives, before stepping into the actual framework and defining risk levels more precisely, it can be sufficient to define risk levels in a qualitative way, for instance as low, medium and high. For example, a railway infrastructure manager could define gradual levels of service to maintain their railway infrastructure depending on the risk level, intending for all trains to be able to run at a low risk level, whereas only the most important rail links may need to run at the highest risk level. Likewise, a higher travel time could be accepted on the same infrastructure for higher risk levels. Generally, agreeing on acceptable levels of risk, carrying out vulnerability and risk assessments as well as utilising stress test frameworks for particular infrastructure and assets are steps that are covered in much more (necessary) detail in the sector specific guidance that can be referred to by the transport professionals. Further discussion on such valuable resources in this context is presented later in this section.

23. The next step in the adaptation planning approach is analysing and understanding the current situation. Of course, each asset or infrastructure is unique in terms of its characteristics and the services it provides. Thus, knowing as much as possible about one’s asset or infrastructure, can provide a good foundation for analysing potential future situations and ultimately for developing relevant adaptation pathways. It is recommended that with the ultimate goals in mind, the current situation is assessed to set environmental, social and economic baselines. This starting point will help assess the results of a scenario where there is no change and will thus help envisage possible futures [0]. Therefore, it is important that transport infrastructure asset owners and managers carry out this step with due diligence, possibly through in-depth consultations within their organisations to gain a full extent of knowledge so that they have a good understanding of the requirements of this stage for their individual assets. To do so, they can analyse historical information and drivers that have resulted in the current conditions and assess how the asset has been managed or what actions have been taken to solve the current problems. This information should be used to design and develop potential future management actions. However, one key point to consider is that historic information is not always enough.

24. Transport planners and operators usually consider the impacts of past extreme weather events. Recent work in Europe has indicated that several standardised approaches for factoring extreme weather parameters into the design of transport infrastructure are still applying historic weather data that is already out-of-date. Over the past two decades, the climate has changed severely and thus, the historical weather data can no longer fully reflect the current climate risk, let alone the way climate risks will change over the useful life of a transport system. Some critical transport infrastructures such as bridges have long lifespans and thus, it is now recommended that full asset lifecycles are considered in climate adaptation. It is vital that climate change scenarios and their implications for average and extreme precipitation and temperatures along with the likely frequency of extreme events in the future are accounted and implemented in all stages of design and implementation [0].

25. The third step of the adaptation planning approach is to analyse, develop and assess the possible future scenarios. This stage builds on the previous stage and is informed by climate projections to predict the state of the environmental, social and economic factors in the future. Projected future scenarios can then be tested against different adaptation options to understand if they are desirable options or not. The stress test framework [0] can also be

used at this stage as the framework is designed to investigate a number of different potential scenarios. This stage also includes assessing the risks associated with the possible futures, to understand where there are (unacceptable) risks that may require action. Overall, this stage can be very helpful in developing various management responses and thus acknowledging other factors that influence a management response, such as market and social values or future policies. Regardless, it must be noted that the future is always going to be uncertain but through the development of a range of scenarios, several different options can be tested to determine if they are flexible, robust, or both [0].

26. The fourth and fifth steps of the adaptation planning approach are to develop the pathways and implement, monitor and learn from them. These steps are discussed in-depth in ECE/TRANS/WP.5/GE.3/2023/2. However, it is expected that the transport infrastructure owners and asset managers have a good understanding of the first three stages in order to appreciate and implement the next steps. Of course, the former could be a challenging task in itself and thus it is recommended that transport infrastructure owners and asset managers encourage stakeholder engagements and the inclusion of experience and tacit knowledge to ensure that the acquired knowledge/skill set aligns with the existing management approach, and the specific context and asset portfolio [0]. Also, it must be remembered that, climate-proofing or adaptation measures may vary in their complexity and straightforwardness across different operations, assets, and systems. While some cases may require relatively straightforward and immediate measures, others could greatly benefit from adopting an adaptation pathways approach. Targeted guidance is essential for situations where uncertainty or delayed investment justification exists. In situations where there is significant uncertainty about future climate conditions, impacts, or the effectiveness of specific adaptation measures, an adaptation pathways approach is highly valuable. This approach allows decision-makers to assess a range of potential future scenarios, consider multiple adaptation options, and adjust strategies as more information becomes available. Similarly, in some cases, the full-scale implementation of adaptation measures might not be immediately justified due to various factors, such as budget constraints or the perceived magnitude of climate risks. In such instances, an adaptation pathways approach can help identify incremental and flexible measures that can be implemented over time, allowing for adaptive management and progressive climate-proofing as investment justification becomes more evident.

27. It must be remembered that transportation systems are interconnected and complex systems that can have changing patterns of ownerships, operational control, use, a variety of asset ages and lifespans along with the ability to be further engineered and developed over time. Hence, a number of potential interventions and methods are required for the adaptive management of transport networks in order to assess their effectiveness and phasing over time. The idea of a risk-based, circular approach, where interventions are planned, implemented, monitored and assessed as the initial phase for new action planning is now increasingly becoming accepted. In this regard, some national transport authorities such as Trafikverket, Sweden, and several international bodies such as PIANC have recently started to show developments in their adaptation strategies [0]. Additionally, the PIARC Climate Change Adaptation Framework, 2015 is currently being updated to incorporate adaptation pathways as an approach for assessing deep uncertainties, and as a continuous process of assessing and implementing adaptive measures as new information and changing circumstances arise [0].

28. Further, as indicated earlier, this guide stresses that transport infrastructure owners and managers who are interested in developing adaptation pathways must have a detailed understanding of the vulnerabilities of their individual assets and should have performed the appropriate risk assessments on their individual assets. To do so, they could possibly use risk assessment frameworks and guidance that have already been developed and recommended by organisations such as PIANC (World Association for Waterborne Transport Infrastructure), PIARC (World Road Association) and similar, or even national risk assessment frameworks as well as the stress test framework [0]. Moreover, in 2019, the International Organization for Standardization (ISO) introduced its first-ever international standards aimed at managing the effects of climate change. These standards, ISO 14090 titled "Adaptation to climate change — Principles, requirements, and guidelines," and ISO 14091 titled "Adaptation to climate change — Vulnerability, impacts, and risk assessment," offer

organisations guidance in identifying and effectively addressing the risks and opportunities associated with climate change. These standards facilitate policy formulation and implementation and are aligned with the United Nations' Sustainable Development Goal on climate action (SDG 13). Utilising the information and expertise from these useful resources could be carried out as part of the steps 1-3 highlighted above. Transport professionals should understand the risk and opportunities that exist from the current climate, as part of step 2, and for the future climate, possibly consider a range of several future scenarios, as part of step 3. This would include comprehending the environmental factors that affect the current systems as well as identifying what the most critical issues are. Transport infrastructure owners and managers should then look into what decisions that affect these risk and opportunities they have / do not have control over. This would also involve understanding the high and low probability climate scenarios. The localised and systemic implications as well as an assessment of what could fail (vulnerabilities and potential points of failure within a system or infrastructure) on a pathway towards a particular scenario must be assessed and understood [0].

29. Certainly, as part of the risk assessment, identifying the current climate hazards, the vulnerabilities and adaptive capacity is essential for effective adaptation planning. This can be done by reviewing and analysing the level and nature of changes in the climate hazard and vulnerability which would need to be managed over the useful life of the transport system or asset. It must be noted that for identifying appropriate adaptation options, it is crucial to understand the fundamental nature of a risk and its root causes. For the analysis of vulnerabilities, climate impacts on transport can be distinguished as:

(a) Impacts on transport infrastructure and rolling stock;

(b) Impacts on operations and level of service provisions, including supply chains;

(c) Impacts on mobility behaviour, patterns and demand;

(d) Impacts on health/wellbeing of passengers and personnel.

30. Transport professionals should have a good understanding of the environmental, physical, social and organisational elements to deliver mobility for people and goods in order to fully grasp the overall vulnerabilities. Also, the vulnerabilities need to be considered along a range of different levels of climate change impacts in order to find a way to most effectively respond to them. This includes identification of the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variables and extremes. According to PIARC [0], vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed (existing or future exposure); and the degree to which infrastructure is affected, either adversely or beneficially, by climate-related stimuli (sensitivity). The PIARC Framework also notes that, a vulnerability assessment is expressed as a function of three factors that can be combined in various ways to assess vulnerability, comprising exposure, sensitivity and adaptive capacity (or ability of the system to successfully respond to climate change), according to available information (e.g. use of quantitative, semi-quantitative and qualitative information tools) [0]. Vulnerability is therefore where a climate hazard may lead to an impact, and evaluation of what is a tolerable risk level is part of the overall vulnerability assessment. Thus, it is vital to consider both the vulnerabilities from direct impacts on transport systems and the resulting cascading effects such as the further impacts on the services or the infrastructure upon which the system depends. For example, power (electricity) supply for electric vehicles and their supply chains. As part of conducting the vulnerability assessment, particular attention should be brought to the choice of climate change scenarios, the definition of risk levels, and the identification of thresholds of impacts affecting the level of vulnerability. Interdependencies between transport assets or between climate change impacts should also be considered carefully [0].

31. The UNECE stress test framework [0] offers practical guidance for implementing one or more stress tests on transportation systems. The framework highlights the significance of societal consequences that may occur because of losses in service due to disruptive events (e.g., natural hazards such as floods, heavy snowfalls). Thus, the framework suggests that transport infrastructure should be managed effectively to minimise the consequences of extreme events while considering available resources and potential return on investment. The

framework demonstrates how stress tests can be applied to assess whether an intervention program is necessary to maintain an adequate level of service for transport infrastructure amid climate change hazards. Stress tests are particularly valuable in gauging the resilience of the transport system in specific scenarios, evaluating its performance and its ability to maintain the specified service level for which it was designed. Integrating stress tests into an adaptation plan can offer essential insights into addressing various impacts within a transport system. These tests can contribute early to an adaptation plan and also during the formulation of a more comprehensive strategy. Some components of the stress test may involve techniques such as risk assessment, vulnerability analysis, or threshold analysis.

32. Moreover, analysis of the system and how it has performed during extreme weather events in the past can help offer insights into potential future vulnerabilities. This analysis can be carried out based on traffic incident reports, maintenance records, after-action reports, emergency reimbursement forms and cross-departmental interviews [0]. Overall, it is important that transport professionals use this step to identify ways to address the existing drivers of vulnerabilities of the transport and related infrastructures under current conditions. It has been suggested several times in the past that adaptation is most effective when both the root causes and the symptoms of vulnerabilities are addressed, specifically in those situations where practices and goals need altering as they are either no longer suitable or needed under the changing climate, and thus transformational adaptation is needed [0].

5. Challenges associated with the adaptation pathways approach

33. Even though the adaptation pathways approach has multiple benefits, there are also some challenges associated with using this method that must be noted.

34. Similar to the use of any other typical adaptation plan, with the implementation of adaptation pathways, there may be a lack of clarity in terms of the legal, financial and institutional implications of decisions and who would be responsible for associated impacts, costs and risk mitigation. This is a common issue with cross-jurisdictional funding and risk management structures. A study on overcoming cross-scale challenges to climate change adaptation for local government with a focus on Australia revealed that different councils respond to climate change and address planning in different ways. Without clear information on related jurisdictional responsibilities, the legal responsibilities remain unclear. Such a challenge could be overcome through the creation of a clearly defined mandate (that includes legal as well as political responsibilities), which results in a well-coordinated planning response. It should be clear as to who is responsible for planning for climate change impacts or the extent of the problem. Further, creating a consistent business case framework that utilises multi-criteria analysis points (such as cost benefit analysis) can assist with the documentation of necessary evidence for attracting and gaining political support that is needed for decision-making [0, 0].

35. Determining critical decision points such as adaptation triggers, thresholds and tipping points can be a difficult task under the different climatologic and socio-economic scenarios, especially for hazards that have a large natural variability (for example droughts and storms). It is complex to monitor these hazards, mainly due to the lack of observations of extreme events. For instance, in the case of climate change induced changes in peaks or river discharge, monitoring data and further research has demonstrated that the natural variability in river discharge is so high that even when rapid (but not extreme) climate change is assumed, it can take 30 to 40 years before the climate change signal can actually be filtered in a statistically sound way from monitoring data of river discharge. Practically, to overcome such an issue, research is needed to find alternative approaches as well as parameters for filtering out the climate change signals from river discharge measurements. To accomplish such a goal, data-based detection of changes in observed events could be combined with exploration of possible future events through scenarios and modelling. Alternatively, large ensemble climate experiments might be able to offer a different approach to better quantify the changing probability of extreme events [0].

36. It is challenging to promote wider societal commitments in situations of low predictability. Adaptation pathways make it clear as to what measures should be taken in the short-term and sketch possible future measures applicable for longer term. With regards to the future measures, the decision to implement them may not be taken till there is certainty

about future physical conditions (such as the happening of dramatic events) taking place. This implies that societal anticipation to adopting these measures is hindered. For example, water supply may become limited at some point in the future, but the dependency on this limited resource is unpredictable, and this may lead to either an increased demand in the short term or a slower adoption of newer solutions and technologies. Overall, the delay in taking the final decision for the implementation of the measure can either be a net advantage or a net disadvantage depending on the nature of the measure, the costs and benefits for different actors of anticipating the measure, and on the direction the anticipation works concerning the direction that was intended by the measure itself. Therefore, it is recommended that possible trade-offs are considered in planning the right time for making the final decision about the actual implementation of the measure [0].

37. The effectiveness of adaptation pathways may be constrained if stakeholder engagement is limited, leading to a restricted exploration of the approach's full potential. To achieve successful and transformative adaptation, considering ecological and social dynamics and fostering collaborative learning among stakeholders, a broad and inclusive level of stakeholder engagement is essential. Stakeholder involvement should be at the forefront during the diagnosis of adaptation challenges and the definition of objectives. By including diverse stakeholders, adaptation pathways can better capture a comprehensive range of perspectives and potential solutions, promoting greater resilience and sustainability in the face of climate change [0]. However, it is also essential to strike a balance and avoid involving too many stakeholders. Too many participants can lead to challenges in decision-making, coordination, and communication, which might hinder progress. A large and unwieldy group can make it difficult to achieve meaningful consensus and may result in inefficiencies and delays in the planning process. Instead, a carefully selected group of stakeholders that represents key perspectives, expertise, and interests should be involved.

IV. References

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