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Article

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Abstract: Extreme weather damages and disrupts transport infrastructure in a multitude of ways. Heavy rainfall and ensuing landslides or flooding may lead to road or rail closures; extreme heat can damage road surfaces, or cause tracks, signalling or electronic equipment to overheat, or thermal discomfort for passengers. As extreme weather is expected to occur more frequently in the future, transport infrastructure owners and operators must increase their preparedness in order to reduce weather-related service disruption and the associated financial costs. This article presents a two-sided framework for use by any organisation to develop climate-change-ready transport infrastructure, regardless of their current level of knowledge or preparedness for climate change. The framework is composed of an adaptation strategy and an implementation plan, and has the overarching ambition to embed climate change adaptation within organisational procedures so it becomes a normal function of business. It advocates adaptation pathways, i.e., sequential adaptive actions that do not compromise future actions. The circular, iterative structure ensures new knowledge, or socio-economic changes may be incorporated, and that previous adaptations are evaluated. Moreover, the framework aligns with existing asset management procedures (e.g., ISO standards) or governmental or organisational approaches to climate change adaptation. By adopting this framework, organisations can self-identify their own level of adaptation readiness and seek to enhance it.

Keywords: climate change adaptation; extreme weather; adaptation framework; adaptation pathways; resilience; risk management; sustainability

1. Introduction

The global climate is changing [1] and the frequency of extreme weather events is increasing [2–4]. Extreme weather events can cause damage and disruption to transport infrastructure. For example, heavy rainfall can cause landslides or flooding that lead to road and rail closures [5], or increase road congestion or the frequency of accidents [6]. High temperatures can cause numerous problems for railway infrastructure, such as track-buckling, sagging of overhead lines, the failure of electrical equipment or carriage air-conditioning, or lead to service disruption caused by the increased use of blanket speed restrictions to reduce the likelihood of buckling [7–10]. Extreme heat causes damage to road surfaces such as rutting, cracking, and expansion [7,11]. High winds can blow debris such as vegetation onto roads and railway lines, and gales and high seas can damage coastal rail or road infrastructure [12]. Climate projections (e.g., PRUDENCE [13]) show that the climate a particular region currently experiences may well be different to future climatic conditions. As transport infrastructure often has a design life of multiple decades, future climate should be considered when installing new assets in order to avoid unreliable infrastructure or expensive retrofitting. Existing infrastructure may need to be adapted in response to changing climate risks in order to maintain service provision or prevent escalating costs, for example due to rail buckling occurring more frequently in a future warmer climate [14,15].

It is therefore imperative that infrastructure owners and operators of transport assets prepare for current and future extreme weather events and for longer-term climatic change in order to reduce weather-related service disruption and the associated financial costs. This article presents a two-sided framework for use by any transport owner or operator to develop climate-change-ready transport infrastructure, regardless of their current level of knowledge or preparedness for climate change. It is applicable to all levels of an organisation, in any region of any size. The framework is composed of an adaptation strategy and an implementation plan, and has the overarching ambition to embed climate adaptation within existing organisational procedures so it becomes a normal function of business. For those organisations with lower levels of climate preparedness or knowledge of climatic change the framework may be used to raise awareness and bring the climate agenda to the fore at all levels of business. The framework synthesises global best practice in climate change adaptation and incorporates the tacit knowledge of transport specialists worldwide gained from workshops in Europe, Asia and Africa.

2. Methods

2.1. Literature Review of Current Best Practice and Academic Research

Recent high profile meetings (e.g., UN Sustainable Development Goals, 2015; Paris agreement on climate change, 2016), and high profile weather events with pronounced impacts on infrastructure such as Hurricane Sandy, USA in 2012 [16], or the wet winter 2013/14 in the UK [17], have brought climate adaptation strategies to the fore. The European Union has a framework for action on adaptation to climate change (EU White Paper COM (2009) 147), and many governments have National Adaptation Plans [18], which may call on the transport sector to develop and report progress on a regular basis. There are also adaptation plans at local authority and regional level [19], and sector specific initiatives such as the UK-based Tomorrow's Railway and Climate Change Adaptation [20], or the International Union of Railway's (UIC) Rail Adapt project through which the framework presented here was developed [21]. Similarly, PIANC (World Association for Waterborne Transport Infrastructure) is preparing good practice guidance on climate change adaptation for ports and inland waterways [22]; PIARC (World Road Association) aligns climate change adaptation with reducing greenhouse gas emissions from transport [23]; and the International Transport Forum have examined climate change adaptation in the context of performance management and network reliability [24]. Several individual transport operators have proprietary climate change adaptation reports and strategies such as Highways England, UK [25]; Network Rail, UK [26]; Trafikverket, Sweden, Finnish Transport Agency (FTA), and there are regional initiatives for transport adaptation such as Adapting to Rising Tides from San Francisco, USA [27]. For academic reviews of transport adaptation to climate change see, Regmi and Hanaoka [28] and Eisenack et al. [29].

Climate change adaptation plans must incorporate changes to the frequency or magnitude of extreme weather events, longer-term climatic change, and future socio-economic changes in governance, technology, or population [30]. Adaptation planning approaches, typically based on cost–benefit analysis of individual local interventions, are not well suited to these slow-onset changes, especially when coupled with complex systems containing a mix of extremely long-life assets (e.g., bridges) with short-life elements (digital systems assets). Instead, adaptation pathways offer a phased approach formed of sequential actions that are instigated on the basis of changes to risk (not time), with early actions not compromising future actions. Crucially, by considering scenarios from low-regret to worst-case, adaptation pathways negotiate potential stagnation in decision-making due to "deep-uncertainty", i.e., the inability to make a decision about the future because the future is uncertain. Projects such as TE2100 [31] have pioneered adaptation pathways which has led to a rapidly developing field of literature and adoption in projects such as water management in the Netherlands [32] and New Zealand [33]. TE2100 describes short, medium and long-term options for the Environment Agency to manage flood risk in the Thames estuary, UK, with the capacity for these options to change or adapt as more is learnt about climatic or socio-economic changes in the future. Another innovation of the TE2100 process is the "decision-centric" planning approach (Figure 1). By placing the decision at the centre of the planning process there is greater opportunity for stakeholder involvement, a broader appreciation of the problem (instead of a narrowed focus on climate), and fewer resources required for climate modelling [34], leading to practical adaptation measures for the stakeholder [35]. Flexible adaptation pathways are also part of New York City's climate adaptation strategy [16], and they have been applied theoretically to manage urban heat-risk [36], changing flood-risk [37] and sustainable water management [38].

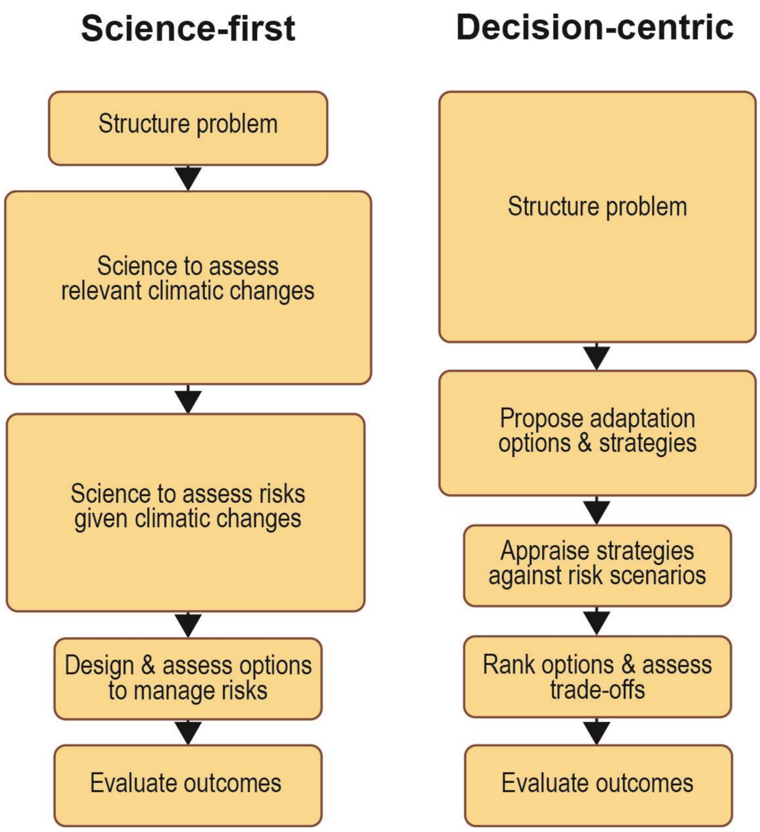

Figure 1. Comparison of science-first and decision-centric adaptation planning. The size of the bubble is indicative of the time each step takes (redrawn from Ranger et al. [34]).

This work also draws on a body of work in management science, business information management, and organisation theory. Beckford [39] proposes an adaptive model of an "Intelligent Organisation" that uses decision needs to drive information system design, and recognises the importance of information to improve performance and long-term effectiveness.

Transport systems are complex and interconnected, with changing patterns of ownership, operational control, use, variety of asset ages and lifespans, as well as engineering systems development over time. Adaptive management for transport networks therefore requires a variety of potential interventions and methods by which to assess both their effectiveness and phasing over time. The concept of a risk-based, circular approach in which interventions are planned, actioned, monitored, and evaluated as the starting point for new action planning, is now becoming accepted with recent developments in adaptation strategies from national transport authorities, e.g., Trafikverket, Sweden, and various international bodies such as PIANC. The challenge remains in how to implement this more widely in a complex and changing multi-agency environment, such as transport, where short-term and long-term goals may not align and actions are required from diverse stakeholders with differing capacity.

2.2. Stakeholder Engagment

Most infrastructure operators and owners have well-defined strategies and procedures for asset and risk management. These may follow the international standards developed by the International Organisation for Standardisation, including: ISO55000 in asset management, ISO14000/9000 for quality assurance, ISO26000 covering social responsibility and environmental impacts, ISO31000 in risk management for safety and financial planning, or ISO22316 for organisational resilience. For a climate change adaptation framework to become part of business as usual it must incorporate climate science and work alongside these existing strategies and procedures. This requires effective two-way communication between climate scientists and transport stakeholders. Transport stakeholders must have a clear understanding of the risk that climate change poses to their infrastructure assets, and the processes controlling the risk and any associated uncertainties [40]. For example, climate change projections suggest an increase in the frequency and duration of heatwaves in the UK [41], which may increase the occurrence rail delays associated with track-buckling in the future [14], but the exact future maximum temperature or the location of rail buckling is uncertain. Moreover, there must be a clear understanding of the definition of "risk" as risk perception varies between individuals and organisations [42]. Equally importantly, climate scientists must apply strategic listening to understand current best practice and operational challenges, and the stakeholder visions for a climate change adaptation framework. This will enable climate scientists to frame climate information and uncertainties in a context relevant for the decision-makers and facilitate a decision-centric planning approach (Figure 1). Stakeholder input is essential to co-create a framework that is suitable for the transport operators and owners, ultimately to ensure the framework is adopted throughout the transport sector.

Stakeholder consultations took place via two dedicated two-day workshops in London, UK (April 2017) and Beijing, China (June 2017), and at workshops held at the UIC Sustainability Conference in Vienna, Austria (October 2016), and the Climate Change Conference in Agadir, Morocco (September 2017). More than 50 organisations from over 20 countries attended the workshops, with delegates predominantly from rail organisations, but with additional consultants and representatives from other transport sectors (Figure 2). Prior to the two-day workshops in London and Beijing, the delegates were provided with a background summary of adaptation issues and information, with an emphasis on rail transport. Each stakeholder event consisted of a mixture of invited presentations and discussion sessions over two days, with subsequent feedback through dedicated electronic channels. The events were structured around the consideration of two aspects: (i) strategic and policy issues; and, (ii) technical engineering matters, thus underpinning the development of resilience through adaptation of both existing systems, and newly built systems or elements. Discussions and knowledge created during the stakeholder consultation events is summarised in the final Rail Adapt report [21], which incorporates written and oral (telephone) interviews, and stakeholder feedback provided on earlier drafts.

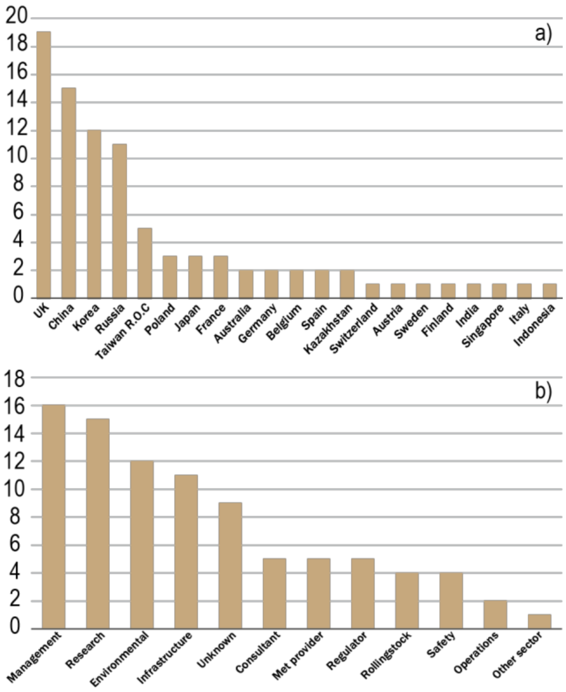

Figure 2. Stakeholder organisations by: (**a**) Location; (**b**) Function.

3. Results and Discussion

3.1. Initial Outcomes from Stakeholder Workshops

Following stakeholder consultations at the workshops in Europe, Asia, and Africa, several key themes emerged:

- Any framework should avoid reinvention by building on what is already underway in existing activities, projects and processes, for example the ISO standards already provide appropriate mechanisms in areas such as asset management.
- Linkages should exist between the adaptation and greenhouse gas emission reduction agendas, thereby widening options for response, as well as with risk management processes in safety and business continuity.
- People from different areas of a business or organisation will have knowledge or experience which will be relevant for adapting to climate change. These personnel can lend support and expertise, and their involvement will increase "buy-in" and acceptance of adaptation more broadly through the organisation.
- Building links with external organisations and stakeholders is vital to avoid maladaptation by reinvention, lock-in, poor understanding of some aspects of the challenges, or by cutting across or undermining the plans of others.
- Stakeholders in different transport modes should work together to develop compatible processes and allow for mutual benefits.
- The process of climate change adaptation should be responsive and iterative, and not linear. The framework should have the capacity to incorporate the new information and experience, and the new questions and challenges this will raise.

3.2. A Framework for Climate-Change-Ready Transport Infrastructure

The key themes raised during stakeholder consultation (Section 3.1) were compared with current best practice and academic research (Section 2.1) to create a two-sided framework to develop climate-change-ready transport infrastructure (Figure 3). The framework contains two sections: (i) the development of an adaptation strategy and (ii) the implementation plan. This structure is based on the experience of transport administrations such as the Swedish Transport Administration (Trafikverket), the Finnish Transport Agency and the PIANC guidance to ports. It is also aligned with the structure of ISO55000 (asset management) and the PIARC adaptation framework. Through experience, organisations have found that there can be too great a step between overall organisational objectives, that have potentially national or international aspects, and the individual adaptation actions that can be implemented in the short-term, which ultimately can lead to stagnation of the adaptation process. Therefore, the purpose of the adaptation strategy is to: help refine and focus the overall framework objectives into specific areas of maximum concern and benefit to the organisation; set the parameters such as time-scale over which they are to be implemented; and, set appropriate priorities.

3.2.1. Adaptation Strategy

Forming the adaptation strategy (right hand side of Figure 3) begins with developing some broad objectives. These would potentially incorporate existing high-level business, social or regulatory objectives on performance, but considered within the context of climate change adaptation. For example, an objective could be that current performance should be maintained more consistently during adverse weather. The strategy then moves forward by identifying the different ways that extreme weather (e.g., heavy rainfall) or longer-term climatic change (e.g., temperature increase over a 30 year period) could impact the transport system, including changing patterns of hazards, vulnerabilities and consequences (economic, social and environmental). Climatic information may be obtained from national meteorological services or global projects such as the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5).

Transport operators may already understand the vulnerability of their infrastructure to climate hazards from comparing performance indicators or fault databases with meteorological data [8,10] or tacit knowledge of industry professionals. This step will also identify where additional data or knowledge are required to determine vulnerability, and the circular nature of this adaptation framework ensures the increasing knowledge can be incorporated in future iterations. This step may also link to existing asset management strategies within the organization, for instance through the local application of the ISO 55000 family of international standards. Liaising with external stakeholders (e.g., other infrastructure operators) here is crucial as infrastructures are part of an interdependent system-of-systems [43] and the weather-related failure of another infrastructure network (e.g., electric supply) may impact transport infrastructure. External stakeholders may also be able to provide information on asset vulnerability under different climatic conditions. For example, Sanderson et al. [44] at the UK Met Office used climate modelling to determine those regions with a present-day climate similar to that which Great Britain would experience in the future, and which have a railway network with similar physical and operational characteristics. By liaising with transport specialists from these countries, operatives in Great Britain may gain understanding of railway operations under different climatic conditions.

Following on, defining the consequences of the impact of weather or climate must consider a range of perspectives. For the infrastructure owner or operator there may be a financial cost of asset repair and passenger or freight compensation for delayed or missed journeys. The failure of transport infrastructure also has wider socio-economic consequences; for example, the UK National Audit Office (NAO) estimated that every train delay-minute costs the national economy £73.47 (2007 costs) [45].

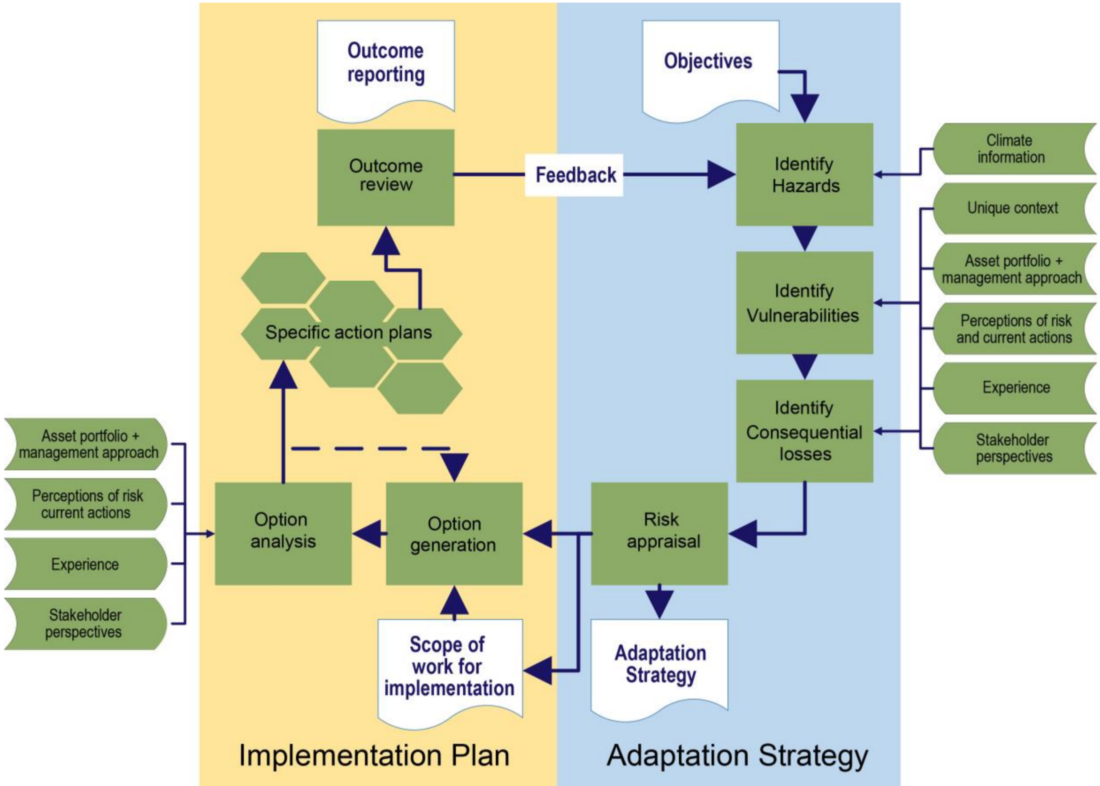

Figure 3. A framework for climate ready transport infrastructure composed an adaptation strategy and implementation plan.

Considering the hazards, vulnerabilities and losses enables a holistic risk appraisal to be undertaken which must determine the most significant risks to the organisation, and which risks must be addressed as a priority to achieve the objectives set out at the start of the process. The appraisal should identify short and longer-term risks, and the financial costs and benefits of interventions or inaction for the transport network, its users, the governance context and the wider national government policy. It is highly desirable to consider adapting to extreme weather and future climatic change as *effective asset management which contributes to business as usual* rather than regarding it as an optional or a separate stream of activity for which extra funding is required. This is not to undervalue the potential of transformational transport infrastructure change but rather to emphasise that these are complimentary, not competitive, pathways to long-term resilience [46]. Weather-proofing transport infrastructure may require increased initial investment, but over the long-term it is essential to prevent escalating costs [14] or expensive retrofitting. It is also important to recognise the tipping point at which the cost of additional adaptation becomes disproportionate to the additional benefits derived. The circular nature of the framework ensures the decisions made in the financial appraisal can be revisited and updated as the forecast hazard frequency or magnitude, infrastructure vulnerability, or socio-economic consequences change. Once completed, the risk appraisal forms the basis of the adaptation strategy by setting out the scope of work for implementation.

3.2.2. Implementation Plan

The adaptation strategy sets out both the objectives to be achieved and the priority risks to be addressed. The implementation plan (left hand side of Figure 3) then draws from this scope of work and considers options associated with each identified risk, within the constraints of the situation (technical, social, environmental and financial). Financial budget will be an influencing, possibly constraining factor, and it will be essential to manage this constraint in such a manner that it does not inhibit the achievement of the desired outcome. The iterative option generation and option analysis phase then proposes approaches that can be used to address the priority risks within the constraints existing. A thorough assessment of options for both the immediate future and longer-term is vital to avoid maladaptation, whereby short-term solutions do not match long-term requirements, or to ensure that early actions do not compromise future actions. For example, to replace an asset that has failed due to extreme weather with another of the same specification may give rapid restoration of service but may miss a cost effective opportunity to reduce long-term risk if that weather hazard is increasing in severity or likelihood. Adaptation pathways, as pioneered by the TE2100 Project [31] should be central to the option generation and analysis. Adaptation pathways enable adaptation to take place in phases, with each phase designed to reduce overall risk to an acceptable level as the environment changes. However, instead of being planned to occur at fixed times, as in a traditional project management approach, these phases can be enacted when the overall risk reaches a pre-determined threshold, as assessed by maintenance inspections, condition monitoring and medium and long term weather forecasts, brought together through regular risk reassessment. Each adaptation phase contributes to a larger plan and is designed to permit flexibility for future options, avoiding actions that may compromise the ability to act effectively in future. Having selected appropriate options to address the priority risks specific actions can be implemented according to those options. The effectiveness of these can then be evaluated over time and the learning fed back into the next cycle of development through a monitoring and evaluation process.

Stakeholder consultations undertaken during the development of this framework showed that different organisations, countries, and cultures approach the option generation and analysis process in very different ways, which potentially reflect disciplinary differences in concepts such as ‘resilience’. For example, there may be an assumption that post-event recovery must include strengthening or replacement of infrastructure to resist all future hazards or extreme events. Academically there are two broad definitions of transport resilience stemming from Holling [47]: (i) engineering resilience, i.e., the resistance of the system to a disturbance, and the speed at which it can return to a steady state, e.g., [48]; and, (ii) ecological resistance, or the amount of disturbance that a system can take before it changes to a new steady state, e.g., [49]. Wang [50] suggests comprehensive resilience should include recovery, reliability and sustainability, noting that disaster could be an opportunity to improve the system. By considering resilience more broadly (i.e., not just in terms of robustness) more effective options can be generated from which to develop the action plan.

Critical to the success of both the adaptation strategy and the implementation plan is the engagement with stakeholders both within different functions of the organisation and externally. For example, expert knowledge may be required for the risk appraisal on climate hazards or asset vulnerabilities, and may need to be brought in from specialist organisations such as national meteorological organisations. Equally, risks are likely to be identified at interfaces between the jurisdictions of different organisations such as access roads to stations or rail depots, which may be under local authority control. It is therefore vital that open consultation between organisations and wider stakeholder representatives be included in the strategy development. In implementation, multi-stakeholder engagement is also critical. Working with other organisations improves effectiveness of the actions taken through coordination and may assist with reducing costs and sharing benefits. An example of this has been in building railway transport resilience to alpine hazards [51].

3.3. Stakeholder Feedback on the Framework for Climate-Change-Ready Transport Infrastructure

Stakeholder feedback on the framework was provided by UIC members as part of a broader consultation on the Rail Adapt project via email messages, or extended written feedback in word documents or PDF reports. Additional detailed feedback was obtained via four telephone interviews undertaken in October 2017 with participants from Asia, Africa and North America, from organisations with different levels of climate adaptation preparedness and different perspectives on climate change. The interviews were semi-structured and included a mix of general questions on framework as a whole, followed by more detailed questions on specific elements as appropriate. The feedback was incorporated into the framework design and the final Rail Adapt project report [21]. Feedback specifically relevant to the framework is described below.

In summary, all interview participants believed that the framework was useful to move the climate change adaptation agenda forward within their organisation or country. Those participants from organisations and countries with lower levels of preparedness for climate change adaptation believed the framework was a useful tool to initiate conversations in this area, and raise awareness of the need to incorporate climate adaptation as business as usual. These interviewees suggested that in the first instance the framework should be taken to senior railway management, chairs, or government officials within the Ministry of Environment or Ministry of Transport to gain high-level support for climate adaptation as business as usual. An interviewee also noted that many organisations in developing countries are unable to give priority to environmental concerns for they have more fundamental daily problems to solve (see also [52]), especially if their knowledge of climate change is not advanced. Support at senior level will be essential to move from a reactive response to extreme events to a proactive adaptation to prepare for extreme events.

Interview participants from North America noted different challenges in moving forward with climate adaptation. In this case the railway infrastructure is better prepared for extreme weather or other unexpected events that may disrupt transport systems (e.g., terrorism). These interviewees also noted the importance of approaching Chief Executives and other senior officials with the framework especially as transport is predominantly a private industry in USA, Canada and Mexico. Both interviewees advocated caution with particular vocabulary used to propose or discuss the framework suggesting phrases like "sustainability" and "extreme weather" rather than "climate change", and "risk and asset management" rather than "resilience" would be preferable. In the current political situation, governors, government agencies and executives are reluctant to actively endorse climate change adaptation initiatives, but do accept the need to prepare for unexpected events. Careful and audience-appropriate use of language will allow the concepts within the framework to be promoted without becoming lost in the debate over anthropogenic climate change.

4. Conclusions

This paper has presented a framework for climate-change-ready transport infrastructure developed following academic review of best practice and via consultation with stakeholders from the transport sectors, incorporating their feedback and tacit knowledge. The framework design places practical decision-making at the centre of the process to prevent the stagnation that can arise when making decisions for uncertain futures, especially given the uncertainty of the extent and impacts of climatic change. The framework recommends adaptation pathways, i.e., a phased approach formed of sequential actions that are initiated by changed risk, and whereby early actions do not compromise future actions. The framework is circular and iterative, enabling new knowledge, or socio-economic changes to be incorporated, and facilitating a review process to measure the success of adaptive measures. Moreover the framework can align with existing asset management approaches such as the ISO standards, or national programs for climate change reporting such as the Adaptation Reporting Power (ARP) required by the UK Climate Change Act 2008. Finally, the flexible framework design ensures it can be used by any transport organisation, regardless of their current level of knowledge or preparedness for climate change. By adopting this framework, it is hoped that organisations can both self-identify their own level of adaptation readiness and seek to enhance it.

Importantly, this framework can be used to embed *climate adaptation as business as usual*, through all relevant functions of an organisation. In that way it does not require a special project or a new budget, but enables adaptation to become part of the normal function of business. Building this new understanding into existing business processes and projects, using the framework approach as described, will enable better results. Ultimately, a well-adapted organisation and infrastructure will have enhanced anticipatory capacity, adaptive capacity and absorptive capacity to deal with the changing world.

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