PROTECTING TRANSPORT SECTOR FROM CLIMATE CHANGE: ANALYSIS AND CLASIFICATION OF ADAPTATION OPTIONS

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Abstract: Observed and projected climate change, such as increases in temperature, sea level rise and the increase in frequency and intensity of extreme weather events, have come to challenge the operation of critical infrastructures (CIs); including CIs in the transport sector, which is an important pillar of our economy and society. Transport, as many other CI sectors, is comprised of complex systems with responsibilities distributed across many different stakeholders. This situation makes integrated adaptation approaches challenging to achieve, requiring appropriate governance and coordinated action. In recent years, climate change adaptation started to emerge as a need for resilient and sustainable infrastructures. Despite the key role of transport and the huge challenges posed by climate change, attention to adaptation for risk reduction at the given sector is relatively low. Good adaptation action requires climate vulnerability analysis and impact knowledge, so it is important that adaptation options are properly identified, evaluated and monitored. This paper aims to detect and analyze global adaptation initiatives in order to classify adaptation options, while focusing on emerging adaptation challenges and opportunities in the transport sector. This will enable stakeholders to improve transport effectiveness and future sustainability, while stimulating what additional actions are needed for climate change adaptation.

Keywords: Climate Change; Transportation; Transport Sector; Infrastructure Protection.

1. Introduction

Recent modeling studies indicate that global average temperatures will increase in excess of two degrees Celsius over the next century [11], [12]. Evidence from the United Nations Intergovernmental Panel on Climate Change (IPCC) indicate that these changes will have significant implications for extreme weather events, development, economic stability, population and ecological health [13], [14]. Climate change issues and concerns for Critical Infrastructures (CIs) focus on climate variations and extreme weather events that are projected to change in magnitude, frequency or duration [15], [16]. CIs are typically designed to withstand weather-related stressors common in a particular locality, but shifts in climate patterns increase the range and type of potential risks. Most infrastructures being built today are expected to last for decades or even centuries [29]. Investing in infrastructures that were not designed to take into account potential changes to future climate can result in significant increases in cost later on and can increase the potential for unplanned outages and failures.

Transport is a critical infrastructure that greatly supports the smooth functioning of society's prosperity and viability of economies worldwide [28]. It facilitates accessibility of services that are vital for business and for the quality of life of citizens. Gradual climate change such as increases in temperature, sea level and rainfall regimes along with the projected increase in frequency and intensity of some extreme weather events will seriously challenge the transport sector. While mitigation efforts remain of great importance, in order to reduce anthropogenic contribution to climate change, a simultaneous focus on CIs adaptation is essential [1].

In this research, we have studied Climate Change Adaptation approaches, strategies and action plans, with a goal to present a survey of adaptation measures applied to the Transport section, along with a detailed classification and analysis of each measure according to established classification methodologies. We have specifically focused on transport sector impacts, searching into national and sectoral adaptation plans for best practices and efficient adaptation options. The rest of the paper structure is the following: A short presentation of transport sector and its impacts from climate change in given in Section 2. Adaptation approaches are presented in Section 3, focusing on adaptation assessment, options identification and classification. In the same section, worldwide adaptation initiatives are briefly presented with a focus to transport sector. Section 4 presents the main contribution of this paper, where adaptation options on transportation are collected, analyzed and classified according to classification methods for climate change adaptations, as proposed in relevant literature. Finally, section 5 concludes our research and proposes further work.

2. Transport Sector

Transport is the movement of people and goods from one location to another [1], [17]. It consists of: (i) **transport infrastructure** (fixed installations including roads, railways, bridges, canals and pipelines and terminals such as airports, railway stations, bus stations, seaports etc.), (ii) **vehicles** (such as cars, buses, trucks, railcars and locomotives, ships and barges, aircraft and drones, etc.), and (iii) **operations** (people, institutions, laws, policies, and information systems) that convert infrastructure and vehicles into working transportation networks [30]. Modes of transport include air, rail, road, water, pipeline and space. In this section, the transport sector and detected climate impacts on different transportation modes are presented and analyzed.

Transport activity is the result of bringing together resources of quite different nature. Service providers put together these resources to make transport services available for different needs, thereby using different transport modes. Regulators at the various administrative levels provide the basic rules to facilitate operations to run smoothly, efficiently and with minimum impacts [1]. Finally, the numerous users make their choices and thereby shape transport demand.

Disruptions to transportation systems can cause large economic and even human losses. For this reason, the transport sector is often characterized as a CI [5], [17]; an important pillar of our economy and society. Since most stakeholders may only have a partial perspective of the system they manage or use [28], it is expected that without any national protection strategy, stakeholders will react autonomously to the challenges of climate change. Given the broad challenges of climate variations and the strong interconnectivity inside the transport sector, such a fragmented approach will potentially lead to great inefficiencies for transport sustainability and resilience to climate impacts.

2.1. Climate Change Impact on Transport

Rising temperatures and extended heatwave periods increase the problems of rail buckling, road pavement deterioration and thermal comfort for passengers in vehicles [5]. Weather extremes generating floods or landslides, which can lead to short term delays and interruptions in all transportation modes, but also long-term interruptions and detouring needs in the event of destroyed land-side infrastructure. Sea level rise can threaten harbors and other transport infrastructure and services in coastal areas. Air transport can be challenged by changing wind patterns, flooding of airport infrastructure, and various extreme weather events. In addition, climate impacts that trigger changes in the organization of society and economy, like different tourist destinations or agricultural productions, can seriously reform transport demand. Table 1 presents, in detail, the climatic pressures and risk of climate change for all transport modes, as collected by several literature sources [5], [17], [28], [30], [36] [37], [38].

The effects of malfunction, disturbance and broken links may stretch far beyond the originally affected area [35]. The transport system is of transboundary character and highly interconnected inside its modes and across modes; hence, disturbances in one part of the network might have a domino effect in other parts too [29]. As such, effects usually extend beyond the transport system, by hindering the ability to deliver reliable services and jeopardizing free movement of people and goods. Depending on the specific case, these interdependencies can result to losses many times higher than direct costs to the transport sector itself [28].

Type		Climatic pressures	Risks
Land Transportation	Rail	Summer heat	• rail buckling • material fatigue • increased instability of embankments • overheating of equipment (e.g. engine ventilation, air-conditioning) • increase in wildfires can damage infrastructure
		Winter cold/ice	• ice on trains and catenary • damage on infrastructure due to low temperatures
		Extreme precipitation	• damage on infrastructure due to flooding and/or landslides • scour to structures • destabilisation of embankment
		Extreme storms	• damage on infrastructure such as signals, power cables, etc. (e.g. due to falling trees, etc.)
		In general:	• reduced safety • increased cost for reparation and maintenance • disruption of 'just in time' delivery of goods and passengers
	Roads (including bridges, tunnels, etc.)	Summer heat	• pavement deterioration and subsidence • melting tarmac • reduced life of asphalt road surfaces (e.g. surface cracks) • increase in wildfires can damage infrastructure • expansion/buckling of bridges
		Extreme precipitation/ floods	• damage on infrastructure (e.g. pavements, road washout) • road submersion • scour to structures • underpass flooding • overstrained drainage systems • risk of landslides • instability of embankments
		Extreme storm events	• damage on infrastructure • roadside trees/vegetation can block roads
		In general:	• speed reduction • road closure or road safety hazards • disruption of 'just in time' delivery of goods • welfare losses • higher reparation and maintenance costs
	Coastal roads	Sea-level rise Extreme storm events	• damaged infrastructure due to flooding • coastal erosion • road closure
	Mountain roads	Permafrost degradation	• decrease of stability • rockfalls • landslides • road closure
Air Transportation	Airports	Summer heat	• greater need for ground cooling • degradation of runways and runway foundations • higher-density altitudes causing reduced engine combustion efficiency • decreased airport lift and increased runway lengths
		Heavy precipitation events	• flood damage to runways and other infrastructure • water run-off exceeds capacity of drainage system
		Sea-level rise	• flooding of runways, outbuildings and access roads
		In general:	• interruption and disruption to services supplied and to ground access, delays and passenger loss of confidence • periodic airport closures • higher maintenance costs
Marine / Shipping	Inland shipping	High river flow (e.g. extreme rain, snow melt)	• problems for the passage of bridges • speed limitations because of dike instability • some restrictions on the height of vessels
		Low river flow (e.g. drought)	• strong restrictions on the loading capacity • navigation problems, speed reduction
		Change in ice cover	In general, shorter periods of ice cover can be expected. Nevertheless, warm and early winters, followed by a rapid decrease in air temperature, may result in thicker ice cover formation and lead to ice jams and damage to infrastructure

		In general:	• disruption of 'just in time' delivery of goods • stopping of inland shipping • welfare losses
	Maritime transport	Sea-level rise	• navigability could be affected by changes in sedimentation rates and location of shoals • more frequent closure
		Change in sea conditions	• more severe storms and extreme waves might affect ships
		Less days below freezing	• reduce problems with ice accumulation on vessels, decks, riggings and docks • occurrence of dangerous ice fog
		Reduced sea ice	• improved access • longer shipping seasons • new shipping routes
	Ports	Extreme storm events	• devastation of infrastructure • interruptions and bottlenecks in the flow of products through ports
		Sea-level rise	
		Floods/landslide	
		In general:	• disruption of 'just in time' delivery of goods • welfare losses • increased cost for reparation and maintenance

Table 1: Climate risk and impacts on transport infrastructure

Adapting the transport system could require substantial infrastructure investments, so mainstreaming of adaptation in infrastructure planning is vital. Work published by the European Joint Research Centre [22], concerning future climate change impacts, presents a comprehensive quantitative assessment of the impacts of current and future climate extremes on critical infrastructures in Europe. The dynamics of climate hazards were analyzed throughout the 21st century using physical models and adaptation tools (2015, 2020, 2050, 2080 predictions). Regarding the implications of climate change for CIs in Europe, results indicate that damages from climate extremes could triple by the 2020s and amount to more than 10 times the present damages of €3.4 billion/year by the end of the century [22] as shown in Figure 1: Economic losses are highest for the industry, transport and energy sectors.

According to this study, heat waves will largely dominate future damages at the transport sector, mainly by impacting roads and rails. These modes of transport will also suffer losses from and coastal flooding, which will drastically increase over time. Inland waterway transport will be impacted by droughts, while sea level rise and increased storm surges will lead to strong increases in damages to ports in the coming century. These projections suggest the need for an adaptation approach with a long-term and systemic perspective, which requires high priority from governance and worldwide adaptation initiatives.

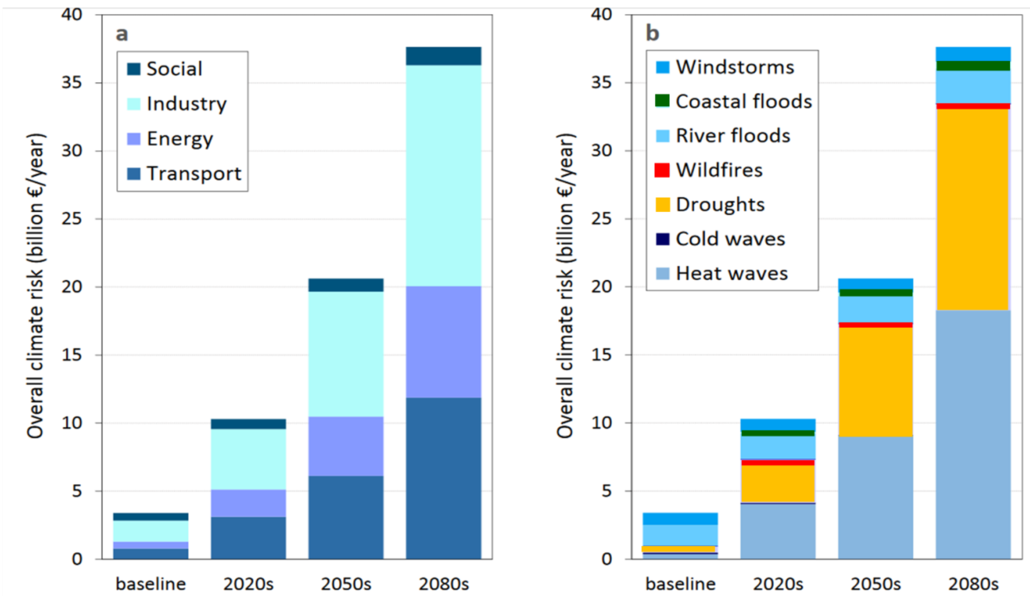

Figure 1. Evolution of climate hazard damages to critical infrastructures in the EU (JRC, [22])

3. General approaches to climate change adaptation

In this section, adaptation principles are discussed; focusing on adaptation assessment (3.1), evaluation and classification of adaptation options (3.2) based on conducted literature research. Subsection (3.3) presents worldwide adaptation strategies, while (3.4) focuses on transport sector. Adaptation consists of actions responding to current and future climate change impacts and vulnerabilities (as well as to climate variability that occurs in the absence of climate change) within the context of ongoing and expected societal change [6]. It means not only protecting against negative impacts of climate change, but also building resilience and taking advantage of any benefits it may bring.

Adaptation and disaster risk reduction share the same ultimate goal to reduce vulnerability to hazardous events [14]. There are synergies to be exploited in closely coordinating disaster risk reduction and adaptation policies. Risk reduction and prevention in the short and medium-term will primarily address socio-economic developments and climate variability to reduce the impacts of natural and technical hazards, while adaptation aims at developing longer-term planning to address climate change impacts [7]. Preparedness refers to the readiness of human and natural systems to undergo gradual change through flexibility in practices and governance, and is a key common element of adaptation and disaster risk reduction actions.

According to [18], [19] adaptation responses and decisions can be categorized as measures and strategies that contribute to: (i) Building adaptive capacity by creating the information (i.e. research, data collecting and monitoring, awareness raising), supportive social structures (i.e. organizational development, working in partnership, institutions), and supportive governance (i.e. regulations, legislations, and guidance) needed as a foundation for delivering adaptation actions; (ii) Identifying adaptation actions that help to reduce vulnerability to climate risks, or to exploit opportunities. These two categories reflect the range of adaptation measures and strategies from which a good adaptation assessment can be developed.

3.1. Adaptation assessment

Adaptation assessment is the practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility [15]. Approaches used in decision-making to assess potential adaptation options can be broadly categorized [24] according to two main steps of analysis: (i) the identification of adaptation measures and (ii) the evaluation of adaptation options.

Identification of adaptation measures distinguishes four targets for strategies that contribute to building adaptive capacity and delivering adaptation actions [19], [20]:

1. *Accepting the impacts and bearing losses*, which reflects a conscious decision that no action is needed to address foreseeable climate hazards, either because the hazards themselves represent a small or acceptable risk with existing measures, or because the exposure unit is not judged worth sustaining and alternatives will need to be considered.

2. *Preventing effects or reducing risks*, which involves the introduction of new measures designed to reduce exposure of assets to new or heightened risks. Such an approach pre-supposes that the exposure unit is of sufficient value to warrant some degree of protection.

3. *Offsetting losses* by spreading or sharing risks or losses, which implies using insurance or establishing partnerships or co-operatives to reduce financial or social losses and minimize exposure to risks.

4. *Exploiting positive opportunities*, which might involve the introduction of new activities or behavior to take advantage of reduced climate risks or a move to a new location to exploit favorable climate shifts.

There are limits to adaptation in terms of the time when action can be implemented in, and in terms of geographical space in which the action will be helpful. There are also inherent limits and uncertainty to the extent to which implemented measures will enhance adaptive capacity and fully protect regions, economic sectors, and communities. Authorities and decision makers face the challenge of deciding which protection level to implement, given their current and expected knowledge of climate change impacts and related damage costs.

Evaluation of adaptation options: Once a set of adaptation options have been identified, the next logical step of analysis is to evaluate these options as a basis for guiding decisions on the eventual selection and implementation of adaptation measures. The World Resources Institute and World Bank guidance documents list a number of evaluation criteria for assessing the suitability of an adaptation option for contributing to a stated objective [25], [26]: (i) Cost analysis, including total costs and cost effectiveness; (ii) Environmental implications; (iii) Secondary or cross-sectoral impacts, externalities or co-benefits; (iv) Social implications, including implications for sensitive and marginalized groups; (v) Short, medium, and long-term efficacy; (vi) Effectiveness at reducing impacts of extreme events; (vii) Effectiveness under different scenarios of future climate; (viii) Limiting factors for implementation or sustainability (e,g., resource constraints); (ix) Consultation with a broad set of stakeholders; (x) Provision for reviewing options based on changing assessments of risk; (xi)Transparency in the process and justification of options selection.

3.2. Adaptation Options Classification

According to European Environment Agencies classification [4], [6], adaptation measures and actions can be grouped under three broad categories:

- *'Grey'* actions are technological and engineering solutions for infrastructure, corresponding to physical interventions or construction measures and using engineering services to make infrastructures more capable of withstanding extreme events. Examples include: building or strengthening of coastal and river flood defenses/dykes, and beach 'nourishment'.
- *'Green'* actions are ecosystem-based approaches that use the multiple services of nature. They use the functions and services provided by the ecosystems to achieve a more costs effective and sometimes more feasible adaptation solution than relying solely on grey infrastructures alternatives. When green adaptation actions are integrated into a spatially organized plan, they are called 'green infrastructure'.
- *'Soft'* actions are managerial, legal and policy approaches that alter human behavior and styles of governance. They correspond to design new policies and procedures, land-use controls, information dissemination, and economic incentives to reduce or prevent disaster vulnerability. Examples include: planning and passing legislation; early warning systems for heat wave risks; natural hazards monitoring; and public information campaigns.

'Green' and 'soft' actions specifically aim at decreasing the sensitivity and increasing the adaptive capacity of human and natural systems to build resilience. These actions are often less resource-intensive and provide multiple benefits. ‘Grey’ actions and innovative technological solutions typically need more funding, and require more research, experience and training to be implemented.

Adaptation has an extremely important role in reducing economic costs of Climate Change. While adaptation has a cost, it significantly reduces the costs of inaction and in many cases has benefits that dramatically outweigh costs [5]. Since it is important to enable cost-effective and proportionate adaptation by implementing the appropriate options, there are several viable options that can achieve effective adaptation, minimizing associated risks and uncertainties.

Addressing adaptation risk and uncertainty, UK Climate Impacts Program (UKCIP) [18], [20], categorizes options as no-regrets, low regrets, win-win and flexible/adaptive management options that target incremental adaptation. On the opposite side, no effective adaptation actions are characterized as maladaptation, which has to be avoided.

- *No-Regrets Adaptation Options* are adaptive measures that are worthwhile, whatever the extent of future climate change. These types include justified and cost-effective measures under current climate conditions and are further justified when their introduction is consistent with addressing risks associated with projected climate changes.
- *Low-regrets options* are adaptive measures for which the associated costs are relatively low and for which the benefits, although primarily realized under projected future climate change, may be relatively large.
- *Win-Win options* are adaptation measures that have the desired result in terms of minimizing the climate risks or exploiting potential opportunities but also contribute to mitigation or other social and environmental objectives. These types of measures include those that are introduced primarily for reasons other than addressing climate risks, but also deliver the desired adaptation benefits.
- *Flexible or adaptive management options* involve incremental adaptation options, rather than undertaking large-scale adaptation. Measures are introduced through an assessment of what makes sense today, but are designed to allow for incremental change, including changing tack, as knowledge, experience and technology evolve.

- *Maladaptation* options occurs when specific adaptation actions either: (1) do not increase resilience and adaptive capacity or do not reduce vulnerability; (2) are not sustainable from an environmental, economic or social perspective (e.g. over-exploitation of water resources); or (3) conflict with other long-term policy objectives. Maladaptation can be prevented by considering both the climatic and the socio-economic elements that constitute vulnerability to climate change.

3.3. Adaptation Initiatives Worldwide

In USA, the Dept. of Homeland Security has developed a Climate Change Adaptation Roadmap and Climate Action Plan, which aligns to the President's Climate Action Plan, preparing the USA for the Impacts of Climate Change [27]. As of 2016, 15 states had completed climate adaptation plans as shown in Figure 2. In addition, several states have created sector-specific plans that consider long-term climate change.

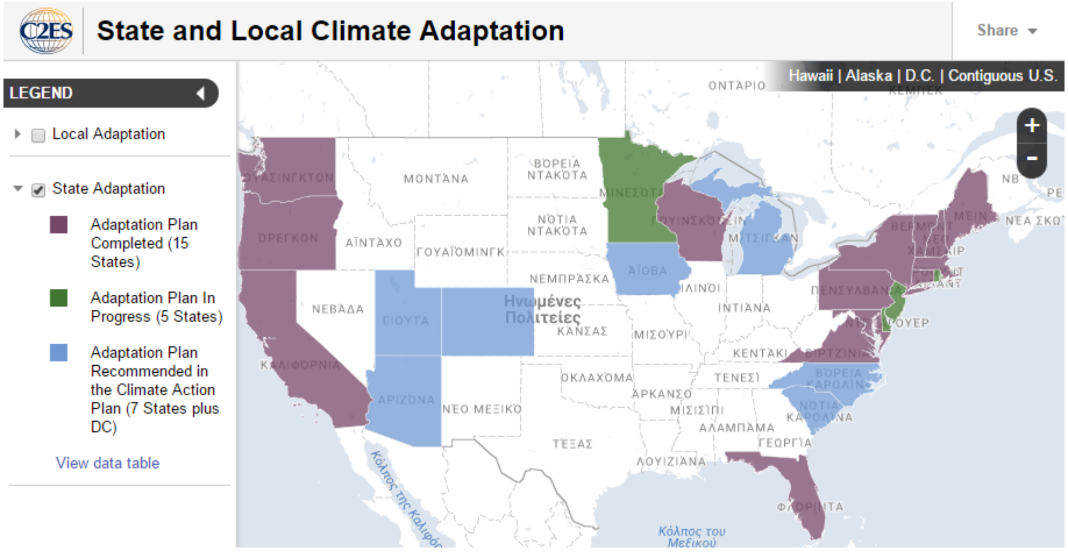

Figure 2. USA State Climate Adaptation Plans (C2ES 2016, www.c2es.org)

European strategy [3], [7] on adaptation to climate change sets out a framework and mechanisms for preparedness for current and future impacts; encouraging and supporting action by EU Member States on adaptation and creating a basis for better informed decision-making on adaptation in the years to come. The majority of EU Member States have adopted national adaptation plans and strategies, outlining their implemented or planned actions to facilitate among other sectors the adaptation of transport to climate change as presented in Figure 3.

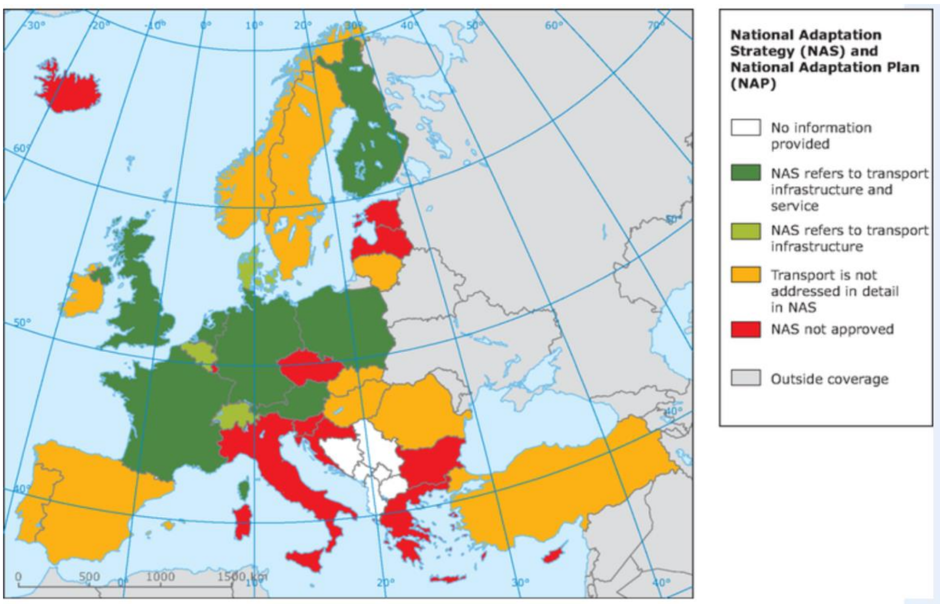

Figure 3: EU State Climate Adaptation Plans (EEA[7])

In Australia, the government has developed the ACT Climate Change Adaptation Strategy [23] to guide efforts in adapting to climate change in a coordinated manner. This strategy identifies the key adaptation policy to help community become more resilient to the projected impacts by communicating the risks and impacts of climate change and incorporating climate change risk considerations and adaptation actions in ACT Government policies.

3.4. Adaptation of transport to climate change

In the past, Transport has already dealt with extreme events causing interruptions, whether stemming from natural hazards or human impacts like accidents and power cuts, and developed strategies to maintain resilience. Therefore, adaptation of transport systems to climate change requires a wide perspective able to embed adaptation into broader transition strategies [5], rather than leaving it to be implemented by single stakeholders like infrastructure managers, operators or regulating authorities in the transport sector.

The transport sector is specifically addressed with some detail in most national strategies and plans studied in this research (including countries such as Austria, Australia, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Poland, Slovakia, Spain, Switzerland, United Kingdom and USA). Most of the national adaptation strategies and plans focus on transport infrastructure issues, and aspects of transport services, such as development of alternative routes and means of transport, traffic management, review of technical conditions for vehicles and their operations, or support to operators in the development of their adaptation assessment and actions.

Also literature research [34] has shown that, in particular, bigger transport stakeholders, like rail companies [32] [33], airports and port authorities, air traffic control operators [9] and others [31], are aware of climate change impacts and the need to adapt, and have started to take action. The prospects of high reconstruction costs, lengthy recovery processes and severe disruptions in the transport system have encouraged infrastructure managers to undertake a comprehensive assessment of the vulnerability of some networks.

4. Adaptation options and implementation actions for the Transport sector

This section presents the main contribution of this paper. In this section, present, common and established adaptation measures for transport are categorized and analyzed, using existing adaptation plans and relevant publications from national plans, US general publications and EU directives [5],[21],[31],[33],[34] and all publicly available national adaptation action plans[1]. Presented measures are categorized and analyzed according to the classification systems discussed in section 3.2. This collection of measures can stimulate further research and discussions among the many different stakeholders concerned with transport adaptation. Section 4 is divided into seven subsections, which are dealing with a different aspects of transport adaptation: (4.1) Effective governance; (4.2) Infrastructure planning; (4.3) Redundancies within and between transport modes; (4.4.) Operational Contingency; (4.5.) Early warning systems; (4.6.) Building Adaptive Capacity; and (4.7.) Collaboration. For each subsection, adaptation options are presented, followed by a summary table, which resumes our research and classification of adaptation options.

4.1 Developing effective transport governance for adaptation

The role of governments is mostly enabling adaptation action at local and regional levels by creating an appropriate framework [2], [3], [26], [27]. This includes effective institutions, knowledge, supportive policy, legal framework, and funding. As such, transport should also be a part of national adaptation strategies and action plans.

Since stakeholders, acting at local, regional or company level, are rather the ones who implement measures like climate proofing infrastructure or operations, it is vital for ruling authorities to create synergies and engage all stakeholders within the transport sector. Moreover, enhancing legislation with national standards for earth and public works and requiring climate risk assessment as prerequisite for the design of new plants, can ensure infrastructure integrity and future protection. Funding for new or existing infrastructure reinforcement should incorporate an adaptation assessment to ensure infrastructure sustainability. Effective Governance measures are presented in Table 2, categorized per adaptation option type classification.

[1] Available on www.climate-adapt.eea.europa.eu & www.c2es.org

Effective Governance Measures categorized by :	Measure Type			Risk and Uncertainity			
Adaptation Option Description	**Green**	**Soft**	**Grey**	**No regrets**	**Low regrets**	**Win-win**	**Adaptive Manag.**
Strategic planning of Sustainable transport development		x		x			
Create an Adaptation framework so as to engage stakeholders within the transport sector		x				x	
Incorporate Adaptation requirements into Legislation & Regulatory Norms		x			x		
Enhance Standards and National/ Regional Requirements		x			X		
Develop National Adaptation Strategy and Action Plan		x					x
Require as prerequisite climate risk assessment and Environmental Assessment for the design of new plants to ensure integrity		x				x	
Ensure Funding for new infrastructure or existing infrastructure reinforcement			x				x
Coordinate Infrastructure Future Planning		x				x	

Table 2: Effective Governance measures proposed in adaptation plans

As we can notice from Table 2, most of measures proposed in effective transport governance for adaptation are ‘soft’ type, expect from funding issues and this is not surprising, since the role of governments is mostly managerial and policy setting, by creating the appropriate framework to enable adaptation action at local and regional level. From the aspect of risk and uncertainty we can notice a variety of options proposed from cost effective to proportionate adaptive management.

4.2 Transport Infrastructure planning

The smooth and effective operation of the transport system relies heavily on hard and extensive infrastructures, which are intended to last long term, in some cases beyond 100 years. Investments are usually costly and with long return rates. An anticipatory approach is necessary for planning new infrastructure, renovation improvements or maintenance. Considering future climate trends now, helps in keeping the costs for adaptation bearable and avoiding future unsustainable development path of the transport system.

Climate change adaptation should be included as a criterion to be considered at all the relevant levels, from network planning to project assessment, by providing concrete methodological guidance on how this integration can be effectively implemented [5]. These are so-called ‘soft measures’ and require relatively low investments. However, further mainstreaming of adaptation into transport infrastructure investments can have substantial implications for the resilience of infrastructure and the costs of adaptation in a long term perspective. In general, it can be expected that adaptation integrated into the design of new and upgraded infrastructure comes at lower cost than adding it at a later stage [29]. Infrastructure Design and Planning Measures are presented in Table 3, categorized per Adaptation option type.

As presented in Table 3, there is a balanced approach between grey and soft measures that can support transport infrastructure design and planning. On the other side, there is only one green measure proposed, which can be justified from the nature of transport infrastructures and networks, since there is always an environmental impact occurring from transport projects development.

From the aspect of risk and uncertainty we can notice a variety of options proposed, the majority of options are measures that minimize climate risk but also have other social and environmental benefits (win-win) and measures with incremental actions for flexible adaptation (Adaptive Management).

Infrastructure Design and Planning Measures	Measure Type			Risk and Uncertainity			
Adaptation Option Description	**Green**	**Soft**	**Grey**	**No regrets**	**Low regrets**	**Win-win**	**Adaptive Manag.**
Revision of obsolete Design and Infrastructure Standards		x		x			
Create New Standards & Recommended Practices for Resilient Infrastructures		x				X	
Improve site/ earthwork design to combat landslide, subsidence, heave or wind damage.	X					X	
Civil engineering regular checks of infrastructure foundations and measures to protect erosion			x				x
Review piping installation to identify which parts of plant equipment may be vulnerable.			x		X		
Strengthen drainage elements and design and improve storm drain capacity			x				x
Proactively inspecting and maintaining guidance for infrastructure assets		x				X	
Use design limits to explore whether measures for heating, cooling, insulating or drying are required.			x				x
Provide specific information/ guidance for staff on working in extreme temperatures or windy weather.		x				X	

Table 3: Infrastructure Design and Planning measures proposed in adaptation plans

4.3. Redundancies within and between transport modes

Designing, building and using redundant infrastructure, like alternative rail links or roads can support transport operation resilience. Build and retain ready to use back-up equipment and vehicles, in case of emergency, and adding backup power/generator capacity in critical facilities are also suggested as redundancy measures. Usually, such a strategy involves extra cost to establish and maintain this redundant infrastructure, which, under normal conditions, might not be necessary. It has therefore probably been a less preferred option, but it is expected to gain importance, in the face of more extreme weather events due to climate change in the future.

Multimodality [5] offers redundancy potential at different levels. If different modes are available, the user can choose which one best serves his/her transport needs, and might switch from one mode to another. Smart and flexible ticketing, which allow passengers to switch operators and modes in the event of disruption, could facilitate this process. Building and retaining ready to use back-up equipment and vehicles in case of emergency and adding backup power/generator capacity in critical facilities can also supports adaptation efficiency. Redundancy Planning Measures are presented and classified in Table 4.

Redundancy Planning	Measure Type			Risk and Uncertainity			
Adaptation Option Description	**Green**	**Soft**	**Grey**	**No regrets**	**Low regrets**	**Win-win**	**Adaptive Manag.**
Design and build redundant infrastructure in vulnerable to Climate change or extreme weather areas			x				x
Design and construct resilient vehicles for all transport modes			x			x	
Explore multi-modality opportunities (like multi modal stations, smart and flexible ticketing options, etc.)			x			x	
Build and retain ready to use back-up equipment and vehicles in case of emergency			x				x
Adding backup power/generator capacity in critical facilities			x				x

Table 4: Redundancy planning measures proposed in adaptation plans

As expected and listed in Table 4 redundancy measures are ‘grey’, since they require more funding and additional resources to establish and maintain this redundant infrastructure. From the aspect of risk and uncertainty options can be categorized either win-win, since redundancy options also offer social benefits for transport users, or measures that offer flexibility and increase adaptive management.

4.4. Operational Contingency

Transport has traditionally developed approaches to cope with the impacts of extreme weather events, with solutions which might also be valuable options for adapting to climate change. Preparing for a risk situation can be done with contingency planning, business continuity and disaster recovery plans for extreme weather events. Emergency reporting and emergency equipment preparedness, surveillance and maintenance plans can support integrity of critical facilities. It is also important to locate records, materials and inventory away from potential vulnerable areas, or even relocate critical assets prior to damage or impact. Last but not least, insurance schemes can support key infrastructure funding and restoration in vulnerable areas. Operational Contingency Measures are presented and classified in Table 5.

Operating Contigency	**Measure Type**			**Risk and Uncertainity**			
Adaptation Option Description	**Green**	**Soft**	**Grey**	**No regrets**	**Low regrets**	**Win-win**	**Adaptive Manag.**
Establish Preparedness and Prevention Plan		x		x			
Business Continuity & Disaster Recovery Plan		x		x			
Emergency Reporting and emergency equipment preparedness			x		x		
Locate records, materials and inventory away from potential vulnerable areas.		x			x		
Provide staff with more/ better PPE e.g. air-flow suits/ helmets for hot weather, heavy snow or storm etc.			x			x	
Relocating critical assets prior to damage or impact			x				x
Surveillance and Maintenance Plans to safeguard integrity		x		x			
Insurance schemes for key infrastructure in vulnerable areas			x				x

Table 5: Operational Contingency measures proposed in adaptation plans

From Table 5 occurs that operational contingency measures can be either grey or soft measures, in order support integrity of infrastructure and transport continuity. Green measures are missing, since it is hard to find green solutions to secure transport contingency. From the aspect of risk and uncertainty we can notice a variety of options proposed from cost effective ones to proportionate adaptive measures.

4.5. Early warning systems

Early warning systems, allow transport managers to prepare for extreme weather events, whether they are induced by climate change or current climate variability. For example, EUROCONTROL Network Manager [9] has developed a natural hazards and weather resilience tool, which provides information about the potential vulnerability to such events of airports and en route sectors in Europe. Warning systems can get valuable support through the application of information and communications technology (ICT) to transport management. This is the case of sensors and devices, which provide real time information on traffic conditions on the network, including the distribution of temperature, vehicle speeds, presence of obstacles, deformations and other surface characteristics [10]. With the support of ICT, this information can be accessed in real time by infrastructure managers, service operators or users.

Furthermore, vehicles and users could increasingly serve as data collectors, in their own right. This would allow infrastructure managers and transport operators to gain unprecedented real-time knowledge about the parts of the transport system they are interested in. Handling these enormous flows of information, requires the deployment of communication technologies linking vehicles to other vehicles and to the infrastructure [10]. Whilst by their vehicles, transport operators and users can receive the information they need on infrastructure conditions, infrastructure managers can get a more detailed description of the traffic situation from users, and communicate to them accordingly. Such exchange of data greatly facilitates traffic management. It also enables passengers to adapt their plans or find alternative transport options. Such measures can also improve the quality of services and have positive co- benefits for all stakeholders (users and operators). Early warning systems are presented in Table 6, categorized per Adaptation option type. As we can notice from this table, early warning systems are grey and soft measures, which require technological innovation and engineering support. However, they are win-win measures since they offer many other social benefits to users and travelers.

Early Warning Systems	**Measure Type**			**Risk and Uncertainity**			
Adaptation Option Description	**Green**	**Soft**	**Grey**	**No regrets**	**Low regrets**	**Win-win**	**Adaptive Manag.**
Fixed warning systems with GPS technology, Meteorological instruments and other sensors to detect extreme weather events			x			x	
Vehicle sensors and devices transmitting real time information			x			x	
User devices which can get or transmit real time information		x		x			
Weather warnings & incident warnings network			x			x	
Warnings and awareness raising for staff on the increased risks during inclement weather.		x				x	

Table 6: Early Warning Systems proposed in adaptation plans

4.6. Building Adaptive Capacity

Global Initiatives, Transnational or European level and national adaptation platforms are making efforts in collecting relevant information for all stages of the policy process and making it more easily accessible. For example, the European Climate Adaptation Platform [8] supports Europe in adapting to climate change, by helping users to access and share data and information on expected climate change in Europe, current and future vulnerability of regions and sectors, national and transnational adaptation strategies and actions, adaptation case studies and tools that support adaptation planning.

Information collected on past weather events and their impacts can be a valuable starting point for assessing vulnerabilities and developing strategies to adapt to climate change. Knowledge-sharing on adaptation best practices and benchmarking implementation case studies can create new opportunities for newcomers. Also providing awareness raising communication, education and training on climate change impacts and vulnerabilities could also improve adaptation performance. Building Adaptive Capacity measures are presented and classified in Table 7.

Building Adaptive Capacity	**Measure Type**			**Risk and Uncertainity**			
Adaptation Option Description	**Green**	**Soft**	**Grey**	**No regrets**	**Low regrets**	**Win-win**	**Adaptive Manag.**
Create a public adaptation Platform		x		x			
Information Sharing on Adaptation Best Practices		x		x			
Benchmark of best implementation of adaptation measures		x		x			
Documenting and sharing institutional knowledge		x		x			
Build a structure informal dataset to better understand territorial and sectoral vulnerabilities to climate change impacts		x		x			
Provide awareness raising communication, education and training on climate change impacts and vulnerabilities		x				x	

Table 7: Building Adaptive Capacity measures proposed in adaptation plans

Building adaptive capacity measures, as listed in Table 7, are soft measures, which are increasing transport resilience to climate change and are most of the times worthwhile to develop. However, our research revealed that overall the information provided on public informative platforms is of a general nature and specific information on transport is scarce. Transport information on these national platforms could be expanded by adding systematic data collection on transport disruption events at the national level. At this stage, significant problems remain regarding availability of data on impacts of hazards on transport systems, because some stakeholders consider this information as confidential, as it could be used to derive legal responsibilities for service disruptions. Obtaining data on impacts, specifically on transport, available in formats required to cross- check with weather information and with data from other stakeholders is quite important for adaptation planning. Finally awareness raising communication, education and training on climate change impacts is key success factor for adaptive capacity of stakeholders.

4.7. Comprehensive collaboration

The collaboration with climate experts can make transport stakeholders aware of the fact that climate-related topics cannot be addressed through traditional, unrealistically deterministic concepts, and that alternative approaches to risk principles would have to be explored. Through closer interaction, transport experts should be able to define their needs for climate forecasts in more scientific terms, and meteorological experts could better understand transport experts' needs and highlight innovative developments in their modelling practices that could provide useful answers. Through cooperation with experts in other fields, transport stakeholders can increase their flexibility in management and decision-making, thus potentially finding innovative solutions. Collaboration options are presented and classified in Table 8.

Collaboration	Measure Type			Risk and Uncertainity			
Adaptation Option Description	**Green**	**Soft**	**Grey**	**No regrets**	**Low regrets**	**Win-win**	**Adaptive Manag.**
Communicating plans and information with the public and stakeholders		x				x	
Cooperation with stakeholders within transport sector to expand knowledge sharing and best practices		x				x	
Interaction of transport experts with other scientists to expand research on adaptation issues		x				x	
Cooperation with experts from other fields to increase knowledge base on climate, science and adaptation		x				x	

Table 8: Collaboration measures proposed in adaptation plans

Table 8 clearly demonstrates that collaboration measures are soft and win-win measures, since cooperation among experts with different backgrounds and expertise have been proved a fruitful and prosperous way to further mainstream adaptation efficiency and transport resilience.

5. Conclusions

Transport systems are complex. They play a fundamental role in the economy and society, and are characterized by the long lifespan and high costs of their infrastructure. These characteristics suggest the need for an adaptation approach with a long-term and systemic perspective, thus also preventing unsustainable development paths and maladaptation.

Several states worldwide have started to put into place Adaptation Strategies and Action Plans with a variety of measures to promote the implementation of adaptation measures in all critical sectors, including transportation. These measures include the provision of information, capacity building, review of technical standards and use of new ICT opportunities. The engagement of all the main stakeholders in the transport sector is of key importance from the perspective of both equity and efficiency, so regulating authorities, policymakers and researchers should make an extra effort to engage stakeholders in their research and information-dissemination activities.

The majority of adaptation measures presented can be categorized to soft type options (60%), while grey options are also quite popular (38%) in the existing adaptation plans. There is a lack of green measures proposed, which is justified by transport sector infrastructure nature and environmental impact. In general, transport sector low-regret and win-win measures are typically measures that increase the resilience of transport systems, while providing additional, advantages in terms of smooth operations, quality of services and efficiency.

Sound design and maintenance practices for transport infrastructure, integration of transport systems, revision of obsolete design standards and information sharing are some of the options described. Tools and measures developed to manage risks and disaster from natural hazards, including early warning systems and contingency plans, can be very useful for climate change adaptation too. Most adaptation action focuses on climate-proofing transport infrastructures. Integrating adaptation requirements into the design of new and upgraded infrastructure comes at lower cost than adding them at a later stage. Another way to ensure transport flexibility is through providing functionally redundant option, which offers a higher capacity and enables flexibility in the event of a disaster or other interruption.

It is important that adaptation measures taken in the transport sector are properly monitored and analyzed. This will enable stakeholders to improve their effectiveness and efficiency of future policy. Finally, co-operation between stakeholders inside and outside the transport sector can help to make use of the knowledge gained in other sectors and to find tailored, innovative and effective solutions for transport adaptation.

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