Risk Assessment of Road Infrastructures as Key for Adaptability Measures Selection

Erica L. Arango, Hélder S. Sousa, and José C. Matos

Abstract Road infrastructures are crucial for societies daily life due to the dependency of other critical infrastructures upon it. Therefore, society expects an uninterrupted availability of the road network. However, maintain this constant availability is often a difficult task as, in the last decades, climate change has significantly affected transport networks, especially due to the occurrence of extreme natural events leading to their disruption. Those events include floods, wild fires, landslides and others, and all of are varying both in frequency and intensity presently and in the coming years. Therefore, there is a clear need for timely adaptation. Regarding these adaptability measures, an important step is needed to quantify how the transport network is directly and indirectly affected by extreme weather events, which can be obtained within a risk assessment. Nonetheless, there are many questions and variability about this topic such as uncertainties in projections of future climate, cause-effects assessment, and how it can be an integration of all these aspects into a single decision-making process. In that scope, this work describes a risk assessment methodology having account the cause, effect, and consequences of extreme events in road networks to identify the major risks and therefore the assets that may be suitable to be analyzed within a selection of adaptation measures aiming at a holistic decision-making support tool.

Keywords Road infrastructures · Risk assessment · Extreme events · Adaptability measures

1 Introduction

Road network is one of the most important components of transportation infrastructure and therefore a vital aspect of development as well as economic growth [1–3]. Society has generated a great dependence on this system and consequently any infrastructure disruptions may have severe consequences for human well-being. Since the road network is designed to operate within a particular environment, the

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system is placed at risk from the damaging impact of the frequency and intensity of some extreme weather events [4, 5], which are expected to increase [6]. In that aspect, climate change represents a new challenge for the decision makers regarding design, construction and operation of road infrastructures [7]. As in most cases, available financial resources are limited, it is especially important to use these resources efficiently. To achieve that, it is imperative to know the potential risk to these systems which involves the correct problem identification [8].

Risk can be analyzed within the perspective of performance of the structure related to its degradation and possible consequences to a network-level failure. In that sense, infrastructure risk can consider climate change as a parameter when determining its influence on hazard determination in both exposure and vulnerability perspective [9]. A careful application of a risk assessment may have significant contributions not only to threats understanding and to related uncertainties but also to facilitate the decision-making process of road investment, planning and design [4, 6]. Most importantly, risk assessment is the basis to implement preparedness actions or adaptation strategies, which are developed according to the infrastructure needs and situation complexity. For instance, identifying projected levels of variations due to climate changes can provide useful information for adaptability planning and maintenance projects.

Adaptation measures are focused on reducing vulnerability and consequences but these measures are conditioned to aspects such as resources, capacities, environment, and authority/legal constraints and requirements. Therefore, the selection and prioritization of adaptability strategies are highly important as not all adaptation options will be possible for a specific climate change risk or local conditions [8]. Hence, the establishment of adaptation strategies is a challenge with a high level of uncertainty associated with climate change effects, especially to identify limits and effectiveness of the measurements [5].

This work focuses on the description of a risk assessment methodology originated by the need to link and integrate disaster risk reduction with adaptation measures, regarding extreme events in road networks. The framework aims at a holistic decision-making support tool. To do so, the work is divided into four principal sections. The second section is focused on describing risk, its assessment methodology and critical climate parameters affecting road infrastructures. Section three provides an adaptability definition, adaptation measures for the major risks in road infrastructure and their classification. Section four proposes an approach to linked risk assessment with adaptability. Finally, the discussion and conclusions are presented in section five.

2 Risk

Risk is defined as a measurement of a probability and severity of the dangerous situation occurrence [6]. In this scenario, climate change effects are often classified as hazards of medium to large impact with a high uncertainty degree as they are constantly changing both in frequency and intensity. Specifically, extreme events may cause a variety of impacts, which are commonly classified into social, economic, and environmental categories [10]. Therefore, within these categories, risk implies the combination of threats, vulnerabilities and consequences. Thus, threat refers to environmental and climate factors (hazards) described by contextual site factors. Vulnerability is closely relating to the link failure consequences, including infrastructure-intrinsic or function factors. Finally, the consequences provided the threat result or effect involving factors such as human life and injuries, economic losses, and reconstruction cost [4, 11].

2.1 Risk Assessment Methods

There is a wide variety of methods and tools for risk assessment. These methods may include among other, probabilistic modeling, statistical analyses of past events, empirical approaches, risk analysis of technological systems and economic theory-based approaches [12]. However, there is a major classification for risk assessment methods based on data type, which dividing it into three main groups: (i) qualitative, (ii) semi-quantitative and (iii) quantitative analysis as shown in Table 1.

All methods have different ways to find the damaged or failure probabilities but they also present transverse key steps established for risk assessment. Methodological steps are proposed based on RIMAROCC Framework [11], the quantitative framework proposed by Mechler and Nabiul [10] and the mathematical formulation for the integrated framework of Mitsakis et al. [14]. The method itself consists of a cyclic process in which there is a constant definition and analysis of its performance. This procedure begins by establishing the risk context, defining the scope and impact criteria. Second the risk source identification, which involves defining impact areas and unwanted events in terms of potential causes and consequences. Third, the risk analysis and evaluation. Then, prioritized the measure implementation regarding the criteria selected in step one. Afterwards, the risk mitigation that implies the options recognition and selection for risk treatment. In the end, the action plan defines responsibilities, resources and performance of the selected measures; and also implies monitoring and review of the action plan.

In fact, the principal steps can be divided into sub-steps as is shown in Table 2. During the procedure, several steps can be addressed at the same time but it is important to preserve the logical structure of the framework. Since there is a relationship between the steps (predecessor and successor steps) and thus obtain feedback from both each step and the entire framework as part of the cyclical process.

The key steps can be applied in general risk analysis and infrastructures but in the case of road infrastructure it is necessary to treat it as a framework. For that purpose, focusing on most vulnerable or critical sections, nodes or structures is required with regard to climate factors. Perhaps one of the most important aspect is the risk identification into the framework. An undefined risk may affect the whole analysis even if another risk was properly considered [11].

Table 1 Risk assessment methods characteristics

Method	Approach	Advantages	Disadvantages	Example
Qualitative	Description of risks in words	Clear presentation options of risk, easily used and allow the prioritisation	Subjective evaluation, does not provide an assessment of the overall project risk exposure. Lack of categories differentiation	Checklists, what-if analysis, probability/consequence matrix
Semi-quantitative	Intermediary level between the textual and numerical evaluation	Use classes instead exact values and is a good basis for discussing risk reduction. Allow to carry out holistic risk assessment	Do not provide quantitative values. Difficult impacts and frequencies assessment	Risk matrix, indicator-based, probability-impact
Quantitative	Focus on numbers and frequencies	Quantitative risk information may be used in cost-benefit analysis of risk reduction measures, also allow modeling sequences of events	Very data demanding, time consuming. Difficult spatial implementation	Quantitative risk assessment (QRA), event tree analysis, probabilistic risk assessment (PRA)

Adapted from [11, 13].

2.2 *Climate Change*

The average conditions variation of climate also known as a climate change, have been affecting the whole world over a long time. Nevertheless, the consciousness of the consequences has only be awakened on the last few decades, especially related to the build-up of greenhouse gases (GHG) by burning fossil fuels. Clearly, the consequences are extended to road network, this being one of the major contributors to fossil fuel consumption [7]. Climate change translates into threats as extreme weather events and gradual changes for the road system. Also, imply different hazards like coastal and urban flooding, heat, cold, drought, and wind, which affect the infrastructure, passengers, and freight [15].

Table 2 Risk methodology steps and sub-steps

Key steps		Sub-steps
1	Context analysis	Establish a general context
		Establish a specific context for a particular scale of analysis
		Establish risk criteria and indicators adapted to each particular analysis scale
2	Risk identification	Identify risk sources
		Identify vulnerabilities
		Identify possible consequences
3	Risk analysis	Establish risk chronology and scenarios
		Determine the impact of risk
		Evaluate occurrences
		Provide a risk overview
4	Risk evaluation	Compare risk against established criteria
		Determine which risks are acceptable
		Identify treatment priorities
5	Risk mitigation	Identify options
		Appraise options
		Formulate an action plan
6	Action plan implementation and monitoring	Develop an action plan on each level of responsibility
		Implement adaptation action plans
		Regular monitoring/review and feedback

Adapted from [10, 11, 14]

The principal concern about climate change is its incremental trend. By the year 2100 an increment of 1770 GtC in the total cumulative carbon emissions is predicted as well as 1.1–6.4 °C of temperature and 0.18–0.59 m rises of the sea level [8]. However, climate change impacts in different way each region of the planet. For instance, the Europe forecast shows for northern Europe largest warming in Winter, with increase on mean and extremes precipitation. Whereas, for the Mediterranean area, largest temperatures in Summer, the mean precipitation decrease and increase in the risk of droughts. Also, in southern Europe, the highest average temperatures will increase especially in Summer. In general, it is also likely to have an average extreme wind speed increase and a decrease on snow depth [3].

2.2.1 Critical Climate Parameters

Road infrastructure may be affected by several extreme events types such as, extreme precipitation, sea-level rise, maximum temperature rises or extreme winds.

Depending on the context these may be temporary or extended [2]; at a structural or service level; in a direct and indirect way [7]. Road networks performance and the critical climate parameters have been studied by several researchers [4, 11, 15–22]. Table 3 summarizes some of the most frequently climate parameters that cause an impact on road infrastructures.

3 Climate Change Adaptation

The implications of extreme events caused by climate change in the transportation system require actions. The repair or reconstruction posterior to an extreme weather event, sometimes hinder disaster relief efforts, affect the economic recovery and further drain the limited financial resources [7]. Not only mitigation actions are necessary, but preventive actions. Consequently, the strategies aim is to increase the resilience of road infrastructures against climate change but preserving their economic feasibility, and ideally considering measures contributing to GHG emissions reduction [22]. In fact, different researches have evidenced how road infrastructure investments in terms of climate change adaptation may even decrease cost estimation of the lifecycle, while also increase the infrastructure performance [5].

Adaptability should be considered as an effective asset management, and not only as an optional or isolated process, in which extra funding is needed. Nonetheless, it is always necessary to identify the tipping point at which the adaptation cost is unfeasible regarding the additional benefits [23]. Hence, adaptation measures are permanently linked to the economic aspect. On the other hand, adaptation itself is a dynamic and inclusive process that involves not only the interaction with many other policies but among road experts, stakeholders and administrators [11].

The adaptation development process can be made in phases, in which each is designed to guaranty the risk reduction to climate change. Therefore, the principal process step is the risk assessment and from this it is possible to identify, evaluate and select one or more options, keeping an acceptable risk level.

The framework also includes a cost-benefit step because not all options can be applied in terms of initial investment, as well as a document that provides the complete action plan, defining the implementation process and responsibilities (Table 4). The proposed methodology offers flexibility in terms of applicability; thus, it can be applied for any type of infrastructure system and to include future options. In the end, the framework provides a set of robust adaptation strategies for several risk scenarios. It is also important to mention that all steps are iterative and can be updated regarding different aspects such as hazard forecast, vulnerabilities and consequences estimation or the cost-benefits quantification.

Table 3 Critical risk factors of road infrastructures

Critical climate variables	Major risk to the road infrastructure	Affectation type
Extreme rainfall events (heavy showers and long periods of rain)	Flooding of roadways	S
	Road erosion, landslides and mudslides that destroys the embankments	M, S
	Erosion (scouring) and damage to bridge supports	M
	Overloading of drainage systems, causing erosion and flooding	M, S
	Reduced surface friction and subsidence of element	M
	Blocking or damage of transportation line	S
	Damage of pavement due to destruction and instability of vegetation along the path	M
	Traffic hindrance and safety	S
Seasonal and annual average rainfall	Impact on soil moisture levels, affecting the structural integrity of roads, bridges and tunnels	M
	Adverse impact of standing water on the road base	S, M
	Risk of floods from runoff, landslides, slope failures and damage to roads if changes occur in the precipitation pattern (e.g. changes from snow to rain in winter and spring thaws)	M, S
Sea level rise	Inundation of roads in coastal areas	S
	Erosion of the road base and bridge supports	M
	Bridge scour	M
	Reduced clearance under bridges	M, S
	Extra demands on the infrastructure when used as emergency/evacuation roads	S
Maximum temperature and number of consecutive hot days (heat waves)	Concerns regarding pavement integrity, e.g. softening, traffic-related rutting, embrittlement (cracking), migration of liquid asphalt, blow-ups	M, S
	Vehicle failure (tyres)	S
	Thermal expansion in bridge expansion joints and paved surfaces	M
	Fatigue of drivers	S

(continued)

Table 3 (continued)

Critical climate variables	Major risk to the road infrastructure	Affectation type
	Impact on landscaping	S
Forest fires	Reduced visibility	S
	Dangerous driving conditions	S
	Structural damage of infrastructure, especially pavements	M, S
	Growing vegetation on slopes is destroyed. It can lead to soil degradation and slope slide	M
Drought (consecutive dry days)	Susceptibility to wildfires that threaten the transportation infrastructure directly	S, M
	Susceptibility to mudslides in areas deforested by wildfires	S, M
	Consolidation of the substructure with (unequal) settlement as a consequence	M
	More generation of smog	S
	Unavailability of water for compaction work	S
Snowfall	Traffic hindrance and safety	S
	Snow avalanches resulting in road closure or striking vehicles	M, S
	Failures in transport control system	M
	Cracks close to contraction joints in the cement concrete pavement	M
	Ice and snow in culverts leading to reduced drainage capacity and water on the road structure or flooding	M, S
	Flooding from snow melt	S
Frost (number of icy days)	Traffic hindrance and safety	S
	Material damage of infrastructure	M
	Technical failure of vehicles	S
Thaw (number of days with temperature zero crossings)	Thawing of permafrost, causing subsidence of roads and bridge supports (cave-in)	M, S
	Frozen culverts may be blocked and cause structural damage	M
	Cracks close to contraction joints in the cement concrete pavement	M
	Decreased utility of unimproved roads that rely on frozen ground for passage	S

(continued)

Table 3 (continued)

Critical climate variables	Major risk to the road infrastructure	Affectation type
Extreme wind speed (worst gales)	Threat to stability of bridge decks	M
	Difficult driving conditions; exposed parts of roads (e.g. bridges) closed due to strong wind gusts	S
	Obstacles on the road owing to fallen trees and other objects	S
	Damage to signs, lighting fixtures and supports	M
Fog days	Traffic hindrance and safety	S
	More generation of smog	S

Adapted from [4, 11, 15–22]
Legend Impacts classification: *S* service-level impact (mobility); *M* material or structural impacts

Table 4 Adaptability methodology

Key steps		Definition
1	Risk analysis	Risk levels and scenarios prioritization regarding capacity and financial constraints
2	Identify options	Identify possible adaptation measures for the nonacceptable risks with their respective limits or constraints
3	Cost-benefits quantification	Making sure that the chosen strategies from step 2 can be implemented and that adaptation cost be viable regarding its benefits
4	Options analysis	Compare strategies across all future scenarios. Define the consequences of choosing 'adaptability' or 'not adaptability' measures, using robust decision-making to determine the regret of each one
5	Adaptation plan	Document adaptation options taking into account the information provided in the previous steps and classifying them by impact reduction

Adapted from [5, 14, 23]

3.1 Identifying Adaptation Options

Establishment of adaptability measures options is not an easy task. Several factors need to be taken into account. One of these factors is that the principal adaptation aim is the climate change risk reduction [5, 10, 14] and not all measures can fit within this objective. Another factor is the that adaptation viability depends on the cooperation between decision-makers and stakeholders, the time scale, climate scenario, location and topography, which results applicable for a very specific case [8, 14]. Finally, the availability of financial resources factor and technology application, because its notion is not much applied in the practical field of engineering [7]. That is why effectiveness measurement is necessary, to monitored over time for all cases, in order to feedback the adaptation plan and improve the learning process in future events [23].

3.1.1 Adaptability Strategies Classification

Adaptability measures can be classifiable into different types, sectors or categories. At different levels, as a component or link/node or at network, which suggest that the measures should not be focused in a specific kind of event but cover the level adaptation needs [2]. Another kind of classification was offered by Hallegatte [24], who defined the follow classification, with the objective to keep as low as possible the cost of a wrong forecast of the climate change effect.

- *No-regret strategies **(NR)**.* Produce benefits even without the presence of climate change
- *Reversible strategies **(R)**.* When it is cheap, it is sensible to add "security margins" to design criteria to future (expected or unexpected) changes, making the adaptation measure more robust.
- *Soft strategies **(S)**.* Institutional or financial tools to cope with future changes directly made by planners.
- *Strategies that reduce decision-making time horizons **(RDMH)**.* Reducing the lifetime of investments, therefore, is an option to reduce uncertainty and corresponding costs.

On the other hand, Tol et al. [25] mentioned that fulfil the main adaptation measure objective of reducing risk, is possible following five adaptation strategies.

- *Increasing robustness of infrastructural designs and long-term investments **(RO)**.*
- *Increasing flexibility of vulnerable managed systems **(F)**.* i.e. contemplate midterm adjustments and/or diminishing economic lifetimes.
- *Enhancing adaptability of vulnerable natural systems **(EA)**.* i.e. reducing other (non-climatic) stresses and/or removing barriers to migration
- *Reversing trends that increase vulnerability **(V)**.* i.e. introducing set-backs for development in vulnerable areas such as coastal floodplains and landwards of eroding cliffs
- *Improving societal awareness and preparedness **(P)**.* i.e. informing the public of the risks and possible consequences.

In general, several action options have been proposed for the most critical risk variables, which are summarized in Table 5, being organized by two mentioned classes.

Finally, the importance of taking into account the limits of each of the adaptation measures is highlighted. These constraints need to be carefully studied and handled in determining feasible options to prepare for climate change.

Table 5 Adaptation measures for critical risk factors

Critical climate variables	Adaptability option	Hallegate class	Tol et al. class
Extreme rainfall events (heavy showers and long periods of rain)/seasonal and annual average rainfall/sea level rise	Provision of timely driver information to 'at risk' routes	R	P
	Raise the height of embankment in flood plains	NR	F
	Additional/fortified adequate slope protection works	NR/R	F
	Increase capacity and size of culverts and cross drainage	NR	RO
	Provide adequate river protection works	R	EA
	Consider increasing waterway and protection works to safeguard bridges	S/R	F/EA
	Increase clearance above high flood level for bridges	NR	F
	Alter design-storm criteria, estimating design flood and stormwater taking account of predicted climate	S	RO
	Ensure effective drainage of surface water from the pavement	R	F/EA
	More frequent maintenance and replacement	S/RDMH	F
	Increase pumping capacity for roads and tunnels	NR	RO/F
	Fortify bridge piers and abutments	NR	RO/F
	Corrosion protection	R	F/EA
	Increase capacity of side drains	R	F
	Add green infrastructure/storm retention basins	NR/R	EA
	Relocation of coastal road to higher place	NR	F
	Elevate/protect tunnel openings and low-lying areas	NR	F
	Provide additional protection to coastal roads, e.g. seawalls dikes	R	F/EA

(continued)

Table 5 (continued)

Critical climate variables	Adaptability option	Hallegate class	Tol et al. class
	Design and construct new bridges or replace old ones	RDMH	RO
Maximum temperature and number of consecutive hot days (heat waves)/Drought (consecutive dry days)	Use stiffer bitumen in pavement to safeguard from high temperature	NR	RO
	More frequent maintenance and replacement	S/RDMH	F
	Alter asphalt composition (heat-resistant paving material)	NR/R	RO/F
	Switch from asphalt to concrete	RDMH	RO/F
	Replace expansion joints	R	F/EA
	Increased albedo	R	EA
	Increased shading	R	EA
	Additional/fortified slope retention structures	NR	RO/F
	Control of soil moisture	S/R	EA
	Vegetation management	S	EA
Forest fires	Place sufficient warning and information signs	R	P
	Alter asphalt composition	NR	RO/F
	More frequent maintenance and replacement	S/RDMH	F
	Provision of timely driver information to 'at risk' routes	R	P
	Vegetation management	S	EA
Snowfall/frost (number of icy days)/Thaw (number of days with temperature zero crossings)	Use thick and strong pavement to safeguard against snow and frequent icing-thawing	NR	RO/F
	More frequent maintenance and replacement	S/RDMH	F
	Alter asphalt composition	NR	RO/F
	Provision of timely driver information to 'at risk' routes	R	P
	Increase capacity and size of culverts and cross drainage	NR	RO/F
Extreme wind speed (worst gales)/fog days	Provision of timely driver information to 'at risk' routes	R	P
	Place sufficient warning and information signs	R	P

(continued)

Table 5 (continued)

Critical climate variables	Adaptability option	Hallegate class	Tol et al. class
	Fortify bridge infrastructure	NR	F

Adapted from [8, 12, 14, 15, 26]

4 Linked Risk Assessment and Adaptability Framework

Based on the topics discussed in the previous sections, the following framework is proposed with the intention of incorporating risk assessment against climate change and the respective adaptation measures, having an account of the current practices and academic researches.

Fig. 1 contains the two-sided framework. On the one hand, risk assessment (I), that considers the identification, analysis and evaluation of hazards, vulnerabilities and losses. Highlighting two fundamental aspects. First, the context and objectives definition, which allows the identification and prioritization of the most significant risks for the whole framework. Second, the omission of the risk mitigation step since the framework objective is not to mitigate the damages but to take actions before damage happens, through adaptability measures.

On the other hand, adaptation strategies (II) instead of risk mitigation. This part of the framework covers everything from the adaptation measures identification to their evaluation regarding risk reduction and the costs involved. It is important to highlight the cost analysis, in order to recognize the tipping point at which the cost of additional adaptation becomes disproportionate comparing its benefits. This section also

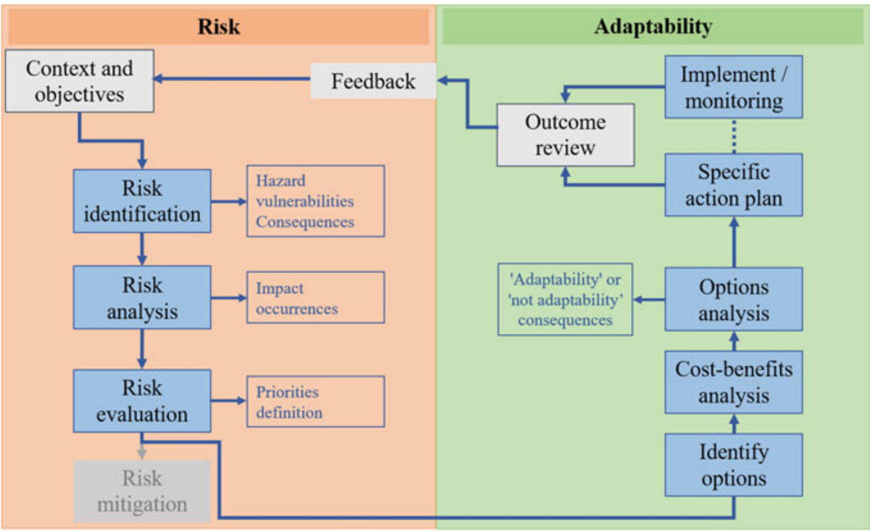

Fig. 1 Adaptability climate change framework for road infrastructures

includes the implementation plan and its monitoring. In which the flexible and iterative nature of the framework is highly important to ensure that applied decisions can be reviewed and updated as predicted infrastructure risks or socioeconomic consequences change. Although this methodology is proposed for the road infrastructure, it offers the possibility to be applied in other infrastructure components.

5 Conclusions

This work presents a framework proposal that allows to incorporate a comprehensive assessment of risks and adaptation options to face the impacts of climate change on road infrastructures. The methodology is circular and iterative, permitting the risk prioritization to achieve the objectives set at the beginning of the process. It is also flexible in terms of socioeconomic changes; review process, to determine the adaptation measures success and allows its application for other infrastructure components. This framework was developed based on academic review of best practices.

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