RISK THRESHOLDS RELATED TO CLIMATE CHANGE IN ROAD INFRASTRUCTURE IN SPAIN

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SUMMARY

The potential risks to road infrastructure posed by climate change need to be studied in greater detail. The methodology utilised for this purpose by the World Road Association (PIARC) addresses, among other issues, the exposure of the assets and services provided by the infrastructure and the probability of the threat or impact occurring. Vulnerability and risk will therefore vary in the future, depending on the different scenarios that are taken into consideration as a result of the pathways that may be taken if one type of mitigation policy is promoted over another. In turn, this is conditioned by the efforts that are made to move forward with the decarbonisation of the energy system.

These threats depend on the variability of the climate. It is likely that the main impacts will come from the increase in precipitation over short periods of time. To assess these impacts, we need to understand the characteristics of the territory where the phenomenon takes place. These characteristics are defined by its drainage capacity, which depends – among other factors – on its orography, geology and vegetation. Thus, for each territory we need to set thresholds, which should be considered as values that trigger action protocols to ensure that the effects of climate events have as little impact as possible.

Identifying these thresholds is not a simple task, and to this end the data from previous events are being analysed. For this article we have worked with infrastructure managers on a specific pilot study to analyse the risk arising from the impact of maximum precipitation within 24 hours on two assets that form part of the road network in the region of Cantabria in northern Spain.

1. INTRODUCTION AND PURPOSE

Climate change is one of the main environmental issues we are facing us today. It obliges us to develop a new approach to land management, in order to get ahead of the adverse phenomena that are forecast, and which will cause significant losses with regard to the provision of road services.

Of all the climate variables analysed, those that are of the greatest relevance for transport infrastructure are precipitation, in all its forms, and to a lesser extent extreme temperatures and thermal oscillations throughout the day.

These climate variables trigger direct impacts on road infrastructure assets, such as overflows on cross-drainage works or bridges, which in the most extreme cases can bring down decks and piers or undermine abutments, piers and slopes. On occasion, they can interrupt the provision of the service by preventing access to certain parts of the road network and can even cut off population centres.

To address these impacts, we propose a methodology involving a vulnerability and risk analysis for services and assets in relation to climate change, with the aim of prioritising an intervention programme that lends greater resilience to transport infrastructure. To this end, it is necessary to focus on different behaviours in the territories in question, in order to analyse the programme’s operation. To achieve this, and for each territory, we need to characterise the thresholds or tipping points of the climate indices that provide warning signs in the locations where there is a high probability of occurrence. In these locations, inspections must be more thorough and corrective measures must be anticipated in order to prevent collapses in mobility, chiefly as a result of damage to drainage works or earthworks.

It is necessary to detail the methodological development that will allow us to characterise the different management thresholds that trigger impacts on the various infrastructures. The aim is for this methodology to be implemented in the different administrations with responsibility for road management, in order to identify, with a certain degree of accuracy and foresight, the appearance of failures in the system. This will make managers aware of the need to systematically document the events affecting the infrastructure, which in turn will help to identify the risks and impact levels and therefore determine the necessary speed of intervention.

This methodology has been designed by the Working Group on Climate Change and Road Resilience, which reports to the Technical Committee for the Environment (part of the Technical Association for Spanish Roads, ATC-PIARC). The Technical Committee comprises professionals from public administrations with responsibility for roads, research organisations focusing on the transport system, academia, consultancy firms, and companies dedicated to the construction and preservation of transport infrastructure.

Some of the earliest and most notable references in the study of potential impacts on roads can be found in the European RIMAROCC[1], ROADAPT[2] and INFRARISK[3] projects. These projects provide guidelines for identifying the main elements that form part of an analysis of the potential impacts of climate change on roads. Subsequently, a number of other European projects (among which CLARITY[4] and FORESEE[5] stand out for their recent completion) have moved forward with the georeferencing of assets while taking into consideration the effects of climate change, in accordance with the AdapteCCa[6] platform developed by the Spanish Meteorological Agency (AEMET).

[1] Risk Management for Roads in a Changing Climate | TRIMIS (europa.eu)
[2] ROADAPT_integrating_main_guidelines.pdf (cedr.eu)
[3] Drupal | Novel Indicators for identifying critical INFRAstructure at RISK from natural hazards (infrarisk-fp7.eu)
[4] Home | Clarity (clarity-h2020.eu)
[5] https://cordis.europa.eu/project/id/769373
[6] Platform for consulting and exchanging information on the subject of impacts, vulnerability and adaptation to climate change. Spanish Ministry for Ecological Transition and the Demographic Challenge (MITERD).

At the international level, there are also many projects that serve as benchmarks for studying the impact of climate change on roads. However, within the scope of this study we will chiefly focus on the work carried out by PIARC. In 2016 PIARC published its first study on this subject [1], where it was proposed an initial version of a methodological framework to help conduct these analyses. In 2019 it published two new documents, [2] and [3]. The first provides an update to the methodological framework, while the second presents a compilation of the main case studies that were collated. The case studies analysed by PIARC include contributions from the Mexican Institute of Transportation (IMT) ([4] and [5]). Lastly, we should also mention three other benchmarks for the study of adaptation to climate change.

The first consists of the reports drafted by the Intergovernmental Panel on Climate Change (IPCC). The IPCC's sixth assessment report places particular emphasis on the protection of critical infrastructure, including energy and transport systems. This infrastructure is increasingly affected by hazards such as heat waves, storms, wildfires, droughts and floods, as well as changes that occur more slowly, such as rising sea levels [6].

Figure 1 outlines the approach proposed by the IPCC for the study of risks. It shows that the "ingredients" of risk analysis in relation to climate change-related impacts are hazards, vulnerability and exposure.

Figure 1 - From climate risk to climate resilient development: climate, ecosystems (including biodiversity) and human society as coupled systems [6]

The second is the European Commission notice [7] providing technical guidance on the climate proofing of infrastructure in the period 2021-2027.

The diagram presented in Figure 2 summarises the methodology followed with regard to adaptation to climate change.

Climate resilience Adaptation to climate change	
Phase 1. Screening	Phase 2. Detailed Analysis
• Sensitivity Analysis • Exposure Analysis • Vulnerability Analysis	• Likelihood Analysis • Impact Analysis[7] • Risk Assessment • Identify adaptation options • Appraise adaptation options • Plan the adaptation

Figure 2 - Diagram of the European Commission methodology.
Own creation, based on [7]

As a third and final reference, from a normative point of view, it is the ISO 14090:2019 standard [8]. The application of this standard may help to show interested parties that an organisation's approach to climate change adaptation is credible. This ISO standard is designed to help organisations develop measures and report on adaptation activity in a verifiable way. Its structure covers pre-planning, the assessment of impacts (including opportunities), adaptation planning, implementation, monitoring and evaluation, and reporting and communication.

2. GENERAL FEATURES OF THE METHODOLOGY: PHASES

The terms used in a risk analysis refer to its constituent components, which are used differently depending on the methodology or guide that is employed. This hinders the dissemination of the results of studies that help decision-makers and the stakeholders or affected parties [9].

Consequently, as a first step to help understand the terminology used, and in order to gain a better understanding of the scope of the study of the risks associated with climate change proposed in this methodology, we have drawn a parallel between the different stages of analysis that comprise the methodology and the different parts of a climate event, transformed into a descriptive story. The story acts as a "mini-narrative" that brings together the factors that need to be studied in order to understand and quantify the potential impact on a road asset or service caused by a current or future climate threat, which could be modified by the effects of climate change. This "story" is the common thread of the methodology proposed within the framework of the ATC-PIARC.

Through the following simple example, which has been transformed into a "story", we present "a possible analysis of the effects of a climate event on a road". It is an exercise in approximation designed to facilitate an understanding of the methodology [10].

[7] This part of the methodology of [7] is equivalent to the severity analysis in the majority of the methodologies analysed, including the one proposed in this report.

Example "story":

Intense rain (**threat**) causes a landslide (**impact**) on a road embankment (**asset**) located in the area of study (**exposure**), due to its geological characteristics, gradient and height (**sensitivity**). This happens every two years (**probability**) and results in moderate social, environmental and economic losses (**severity**), and also has an effect on traffic and nearby urban areas (**criticality**).

Figure 3 below describes the steps that comprise the proposed methodology. The workflow is consistent with the specifications of [1], [2] and [7], and is structured in accordance with the following phases:

Figure 3 - Diagram of the ATC-PIARC Methodology for the Adaptation of Road Infrastructure to Climate Change

Table 1 - Summary of definitions of concepts used in the ATC-PIARC methodology

Asset or Service	*Threat*	*Impact*	*Exposure*	*Sensitivity*	Adaptive Capacity	**Vulnerability**
Element (road Asset or traffic Service) that **receives** the action (Impact)	Element that **triggers** the action (Impact)	**Action** that happens to the road Asset or Service as a result of the Threat	Defined by the place **where** the Impact occurs	Characteristics of the Asset or Service that condition the effect or degree of the Impact (and determine **how** the Impact occurs)	Refers to the factors that increase the Resilience of the Asset or Service, thereby improving the response of the elements that create Vulnerability	Combination of Exposure and Sensitivity. Depends on the characteristics of the Asset or Service and the type of Impact. Not directly associated with any element in the story
	Probability	*Severity* (Seriousness, Magnitude, Consequences)	**Risk**	*Criticality*	**Resilience**	
	When and how many Impacts occur within a period of time	The **extent** and **consequences** of the Impact that occurs	Combination of Probability and Severity. Depends on the characteristics of the Threat. Not directly associated with any element in the story	Characteristics that make an Asset or Service indispensable and which suffer the Impact	Analysis of all of the previous elements in order to optimise the response of the Service or Asset in relation to climate change	

To provide more detail, Table 1 defines the working concepts that support the methodological framework presented in the ATC-PIARC.

2.1. IMPACT ASSESSMENT (PHASE 1)

In this initial phase it is necessary to establish the scope of the study. A particular road administration may be interested in identifying only its most vulnerable assets, in order to develop and implement a general improvement plan (e.g. plans to clean up cross-drainage works) for all of them. In other cases, the administration may wish to go a step further and identify the assets that present a genuine risk to management of the network, in order to propose additional specific adaptation measures. It is also necessary to resolve other questions, such as whether the study includes all of the roads in the country, those in a particular territory, a specific corridor or section, etc.

It will then be necessary to describe the characteristics of the territory where the road network in question is located, as well as the characteristics of the road network itself (infrastructure criticality) and identify the available information sources. Lastly, it is necessary to assemble a group of experts to provide support throughout the assessment process and compare the assessment results against the historical evidence.

Once the scope of the study has been defined, it is necessary to categorise the assets or services as either “priority” or “secondary”, and then break them down by type. This is due to the fact that, initially, it will not be possible to analyse all of the assets in the network; the study requires a certain level of detail which, in turn, means that we have to optimise our efforts with regard to resources. Therefore, we propose first tackling the assets that (on an a priori basis) present the greatest potential risk, in view of the previous studies and projects analysed and taking into account the experience of the group of experts.

The main aim of this first phase is to identify the potential impacts on the assets or services of the section of road that is the focus of the study. We will begin with a list of pre-defined impacts and identify which of them are relevant with regard to the section of road being studied. In order to draw up this list we must identify the main impacts that habitually affect road networks and may be associated with climate conditions (both current and future). To do this, we will start by studying the types of failure that could be suffered by the different assets or services.

For the purposes of this methodology, the climate conditions or set of climate conditions that trigger or have a decisive impact on the type of failure will be known as “threats”. Consequently, a threat is directly related to one or more climate variables, which are studied directly in the process.

2.1.1 Map of threats

In order to study the threats, we need to identify any reference materials for climate variables and climate change projections that can be used to create a map of threats. From the list of potential impacts we can also generate a list of the main threats that are to be studied on an a priori basis. Maps will be drawn up, containing information on the threat in both its current state and for different time frames and scenarios in the future. In turn, the projection of the climate variables implies the selection of a particular RCP[8].

We recommend using the climate indices and variable projections corresponding to RCPs 4.5 and 8.5. RCP 4.5 represents the emissions mitigation pathway that is most likely to apply

[8] The IPCC’s Representative Concentration Pathways.

based on the current implementation of emissions reduction policies. RCP 8.5 is a more pessimistic scenario in which the emissions reduction policies have not achieved the desired effect. These are the pathways for which information on potentially threatening climate variables is available from a variety of sources, studies and projections. We also recommend using the RCP projections for different periods (Historical, 1971-2000; Near Future, 2011-2040; Mid-Future, 2041-2070; and Far Future, 2071-2100). The main reference for carrying out these foresight studies is AdapteCCa, although there are other sources of information – such as [11], Copernicus[9] and the National Flood Zone Mapping System (SNCZI)[10] – that enable the characterisation of impacts and threats.

2.2. VULNERABILITY ASSESSMENT (PHASE 2)

The vulnerability assessment is based on the exposure, sensitivity and adaptive capacity of the assets or services. In the documentary references of [7] the concept of sensitivity refers to the intrinsic characteristics of the asset or service, including its adaptive capacity.

Vulnerability = Exposure x Sensitivity

Assessing exposure consists of determining the extent to which an asset or service, by virtue of its geographical location, may be affected by the different potential threats that are being assessed. Expressed in more casual terms, it consists of determining "whether our asset or service is in harm's way".

For its part, the sensitivity of an asset or service is related to the specific characteristics that determine the extent to which it is affected by a particular impact. In order to assess sensitivity, we have created a sensitivity matrix for each asset or service. Each sensitivity matrix will have different sensitivity factors, which refer to the features that may influence the extent to which an asset or service is affected by a particular impact. For this methodology, adaptive capacity is included in the sensitivity analysis.

The outcome of this phase is a list of the assets or services, categorised according to their level of vulnerability, which must be analysed in order to determine the associated risk.

2.3. RISK ASSESSMENT (PHASE 3)

The risk assessment is based on the probability and severity of the impact on the assets or services.

Risk = Probability x Severity (Seriousness, Magnitude or Consequences)

The quantification of both probability and severity presents a number of difficulties. It should be noted that the main problem we are facing is the lack of available information for these types of study.

The probability or likelihood of a climatic phenomenon occurring is uncertain, and so it is difficult to estimate a specific time frame within which a particular event will take place. Within the framework of this methodology, to determine the probability of an asset or service being impacted we suggest using the calculation of return periods based on the meteorological data for a climate variable, or collating information on previous experiences. In this latter case, the aim is to estimate, in a qualitative manner, the probability of the event or impact

[9] The European Union's Earth observation programme.

[10] A tool designed to support the management of river areas, help prevent risk, aid territorial planning and promote administrative transparency on the part of MITERD.

occurring. A suitable approach would be to identify the maximum number of events that have occurred on the stretch of road in question over as long a time frame as possible. This would make it possible to compare thresholds for risk management.

Severity can be related to the magnitude or intensity of the event, the size of the impact caused by the event, or the consequences should the event occur. This concept is assessed using a scale to categorise the severity of the consequences, and different factors can be taken into account for the purposes of the assessment.

The outcome of this phase is the identification and prioritisation of the assets or services that are at risk. These assets or services will need to be subjected to a resilience assessment and an adaptation plan drawn up accordingly.

2.4. RESILIENCE ASSESSMENT (PHASE 4)

The purpose of this phase is to provide road managers (administrations and companies) with analytical tools to help increase the network's resilience, in order to prevent accidents or reduce the impact that meteorological conditions (both normal and extreme, and both now and for the time frames assessed) are having on the road infrastructure. During this phase we aim to identify and select a number of adaptation measures for particular case studies, while remaining aware of the fact that for each risk there are adaptation measures that may be specific or, in some cases, complementary.

Owing to the lack of resources, it is necessary to select and prioritise the adaptation strategies and responses, adopting a rationalised approach and giving priority to the most effective measures for each case. The methods proposed for this type of approach consist of a multi-criteria analysis (MCA) and cost-benefit analysis (CBA), which are described below. These workflows are those that are most frequently followed in the reference documents ([1], [5] and [7]).

When conducting the MCA we can define certain criteria related to the cost of implementing the measure, the feasibility of implementing it, the potential environment impacts it may cause and its capacity to adapt to new circumstances, among others ([5]).

The CBA utilises a logical and structured process in which all of the different factors (costs and benefits) are quantified. The total quantifiable and non-quantifiable value of the benefits must compensate for the costs in order for a project to be considered worthwhile. There are different types of CBA, although the most complete is the Triple Bottom Line (TBL) model. A TBL analysis assesses a measure or strategy on the basis of its economic, environmental and social impacts, all of which are duly combined [12].

The final step of this phase, and of the methodology, is the implementation and monitoring of the Adaptation Plan. This consists of incorporating the chosen climate change resilience measures into the project's technical design or into the maintenance and operation plans for the assets. To this end, it is necessary to draw up an action plan (implementation and funding) and a monitoring and response plan, which should include a plan for carrying out periodic reviews of the vulnerability assessment and climate risk hypotheses (among others). The aim is to collate a series of indicators that make it possible to assess the progress of the plan and can also be used to review and improve the operation of the methodology. It is also necessary to draw up a communication plan in order to coordinate all of the stakeholders involved.

The outcome of this implementation and monitoring phase will be a complete and organised plan, with structured time frames, to enhance the resilience of the network by improving the assets or services that are at risk.

2.5. PRELIMINARY REFLECTIONS ON THE APPLICATION OF THE METHODOLOGY

As stated above, one of the main difficulties that have been identified with regard to the application of this methodology is the availability of reliable data and information with which to carry out the constituent phases. The biggest challenges are the climate variables or threats that are to be studied (particularly with regard to future projections that include the effects of climate change); identifying the characteristics of the assets or services affected by the events caused by these threats; and the lack of detailed records on impacts to the network caused by the climate. This makes it difficult to set thresholds for establishing categories of exposure and probability, as well as to determine indicators, which are key parts of a climate change adaptation plan. The following sections discuss, in greater detail, how to tackle these challenges using the example of a pilot study set in the region of Cantabria (Spain).

3. THE MOST RELEVANT CLIMATE VARIABLES: PRECIPITATION AND TEMPERATURE

Climate change gives rise to other changes that are going to affect the provision of services across all areas of society. As stated above, the climate variables with the potential to have the greatest impact on the operation of road infrastructure, at both the structural and operational level, are precipitation and temperature. These variables are also the most-studied, and the ones for which there is the most amount of information available in terms of future projections that take climate change into account.

3.1. PRECIPITATION

The AdapteCCa platform can be used to find details on the variable of precipitation, for both Spain as a whole and for each Autonomous Community and province, and broken down by maximum precipitation within 24 hours (Pmax24h) and maximum precipitation accumulated over five days. It provides information on the impacts that may be suffered by the assets on both an occasional and cumulative basis, which in turn enables us to assess the potential threats of landslide to which cuttings are exposed across different time frames.

However, there is hardly any information on the concept of “torrentiality”, which refers to intense periods of precipitation over short spaces of time. The only study of this climate variable in Spain can be found in [11], where the number of variables analysed from previous works has been expanded to include maximum precipitation in intervals of less than one day (3, 6 and 12 hours). The study took into account a control period (1971-2000), three impact periods (2011-2040, 2041-2070 and 2071-2100) and two scenarios (RCP 4.5 and RCP 8.5), with the aim of assessing impact over the course of the 21st century and with reference to three return periods (10, 100 and 500 years).

3.2. TEMPERATURE

The temperature variable has a number of parameters that can determine its effect on road assets. These include minimum temperature, maximum temperature, temperature range, extreme maximum temperature and extreme minimum temperature. In the Cantabria pilot study the implications of this variable were not analysed in relation to the impact on assets.

In any case, it should be noted that it is difficult to work with the data associated with climate variables. In this respect, it is worth mentioning various initiatives promoted by the European Commission to develop climate services, such as the one promoted via the CLARITY project, which aims to simplify access to climate-related information. Ultimately, however, problems related to the maintenance of the applications mean that the data have to be processed on a case-by-case basis, which makes it difficult to access the information.

4. CASE STUDIES OF THE MAIN ASSETS AFFECTED BY THE PRECIPITATION VARIABLE: PILOT STUDY

Around the world, numerous road assets are becoming more vulnerable to climate change [13], much to the concern of the scientific community and governments. In Spain, 45% of the main road network and 4% of the total road network have suffered some form of climate-related impact [14]. The region of Cantabria is no exception: various studies have documented the increasing number of climate-related impacts (in terms of both extreme events and processes that occur more slowly) on infrastructure.

In order to demonstrate a practical application of the methodology described above, we carried out a pilot study in which we analysed two assets located in the Autonomous Community of Cantabria (see Figure 4), specifically on the A67 (Cutting_A67_km175) and N623 (Cutting_N623_km117) roads. In this pilot study the climate variable analysed is precipitation, specifically PMax24h.

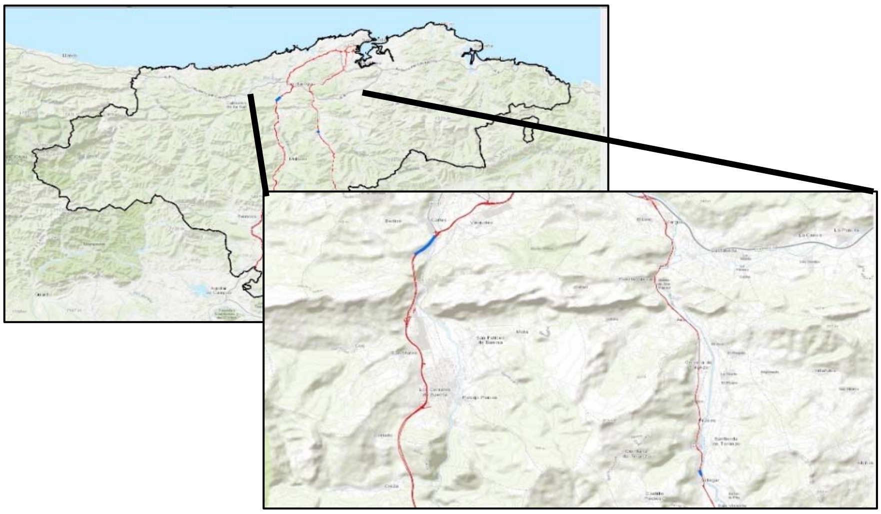

Figure 4 - Location of the two assets studied within the region of Cantabria

The region of Cantabria is located in northern Spain and has a population of 585,222 (2022 census). It is a coastal region that also has a mountainous topography owing to the presence of the Cantabrian Mountains. Consequently, it has a high level of climate variability, which ranges from the temperate oceanic climate on the coast to the warm, summery Mediterranean climate that can be found inland.

The Government of Spain has 600 km of strategic roads in this region, which provide access to the main healthcare, tourist and commercial services. The network is managed by the Directorate-General of Highways, which forms part of the Ministry of Transport, Mobility and Urban Agenda (MITMA).

Historically, Cantabria was connected to the Meseta region and central and southern Spain by two roads: the N-611 from Palencia to Santander and the N-623 from Burgos to Santander. Due to the large volumes of traffic (more than 60,000 vehicles/day) on the final section of the N-611 between Torrelavega and Santander, Cantabria's two largest population centres, in the 1980s work began on a new, more advanced road: the A-67 highway from Santander to Torrelavega. Construction was completed in 1990. The road was subsequently extended out to Palencia and became the A-67 motorway upon the extension's completion in 2008.

Today, the A-67 is the main artery connecting Cantabria to the Meseta region and on into central and southern Spain, and also performs the vital function of providing accessibility throughout the region it serves.

One of the two assets studied, Cutting_A67_km175, is located on the section of road linking Torrelavega to Los Corrales de Buelna Norte, which was opened in 2000. This section of road acts as a duplicate of the Torrelavega bypass and – importantly – is located between the tunnel of Las Caldas de Besaya and the viaduct above the road linking Cartes to Villanueva de la Peña. The terrain is rugged, with gradients of 8%.

The other asset studied, Cutting_N623_km117, is located on the N-623 in the municipality of Entrambasmestas. Although the terrain is also rugged, this particular section of the road runs parallel to the River Pas, with the river on one side and slopes with steep transverse gradients on the other. The road's longitudinal gradient is low, and it is used by traffic of a more local nature.

In a number of places on these two roads, intense storm precipitation can saturate the soil and cause the embankments or slopes to become unstable, giving rise to landslides. Rock fall can also occur in fractured zones, potentially resulting in full or partial closure of the road to traffic.

After analysing the potential impacts of precipitation, the following are of particular note:

- Service affected by intense precipitation, potentially resulting in interruptions to traffic.
- Detachment of rocks and/or earth from the slope. This could be particularly significant in areas of karst terrain.
- Translational or rotational (deep) slides.
- Surface sliding of the slope.
- Settlement and overturning of retaining walls.
- Settlement of embankments due to submersion as a result of the foundations failing or collapse of the embankment body. This may also result in deformation and/or full or partial breakage of the road surface.
- Decreased road safety caused by water build-up on the pavement due to intense precipitation.
- Increased number of problems related to scouring, affecting the piers and abutments of crossings.

5. PRECIPITATION THRESHOLDS: PILOT STUDY

To assess exposure (vulnerability phase) and probability (risk phase) for the pilot study proposed it is necessary to set thresholds, which depend on each variable, climate index or threat and are specific to each territory. These thresholds will be set in accordance with duly recorded and documented experience, and must be consistent with the study area.

One of the factors that may mark a difference between the various territories, with regard to establishing thresholds that define where and when an impact caused by a climate event will happen, is the existence of man-made terrain. The same amount of precipitation in two areas with different capacities for retaining or absorbing a given amount of rain, owing to the sponge effect of soil that is well-protected by vegetation, could cause the thresholds established for an impact to vary greatly. It may be the case that areas with lower precipitation suffer greater impacts than areas with higher precipitation, due to the fact that their territorial characteristics are determined by the land planning regulations or because they have lost part of their functionality with regard to the provision of ecosystem services.

Depending on the resources available, thresholds can be established at different levels, whether national, regional or local. Logically, setting thresholds with a higher spatial resolution (i.e. within a smaller territory) will make it possible to identify the risks associated with climate events more precisely, while also requiring more time for analysis.

In order to increase the level of knowledge, and thereby establish a more suitable categorisation of exposure and probability levels, it is necessary to have a department that systematically inventories climate events and the effects that have occurred in the past, as well as those that will occur in the future.

The records made must specify, at a minimum, the location and date of the occurrence; the climate data for the “triggering” threat; details of the element affected; a description of the damage suffered; and details of the costs of repair or replacement. As stated above, this information will make it possible to establish thresholds, which will aid the task of preparing to mitigate the potential effects of climate change, enable analysis of the causes of the impacts and make it possible to anticipate future impacts.

Some countries have made a great deal of progress in the characterisation of these events, mostly with regard to hydro-meteorological phenomena (which are the ones that have the largest socio-economic impact; some 98% of the total, according to [5]). Mexico counts with departments that monitor climate variables and work with future projections that take into account the variability imposed by climate change. They predict that not all of the future climate changes will be of significance to the local or regional transport network, although the rate at which these impacts occur will increase.

5.1. EXPOSURE THRESHOLDS IN THE PILOT STUDY

To assess the exposure of the assets studied we must begin by selecting the threat that is posed to them and the impact that will occur. In this case we used PMax24h, as the threat that can cause rock fall in the two cuttings studied. To this end we generated a map of threats, in which we established categories of exposure based on specific thresholds that were set in accordance with duly recorded and documented experience and are consistent with the study area.

In order to carry out this pilot study, the State Roads Department in Cantabria provided data of events previously recorded in the area. This information was then linked to PMax24 and made it possible to establish the reference thresholds. Using these thresholds we established five threat categories: Very Low (1), Low (2), Medium (3), High (4) and Very High (5). By cross-referencing these with the location of the assets, we were able to determine their exposure within the context of our study (see Table 2).

Table 2 - Matrix of exposure to PMax24h (mm/day), Cantabria pilot study

Exposure	Very Low	Low	Medium	High	Very High
PMax24h (mm/day)	< 25	25-30	30-40	40-60	> 60

Based on these thresholds, the asset's exposure will be determined by its location and by the threat for each of the periods and scenarios established in the methodology. The asset's vulnerability to climate change can then be calculated based on this exposure and its sensitivity.

5.2. PROBABILITY THRESHOLDS IN THE PILOT STUDY

With regard to determining probability, there is potential for conflict in relation to the scope of the assessment. In some cases, it is the probability of the threat occurring (e.g. PMax24h above a particular threshold) that is analysed, while in other cases the analysis focuses on the probability of the impact, damage or effect occurring. In general, and owing to the difficulty of obtaining data to support the assessments, the information that is available in each case should be used.

This pilot study aims to investigate the level of occurrence for the impacts in relation to the assets; consequently, for the probability assessment, in addition to studying the events (which was already done in order to establish the exposure thresholds) we also calculated the return periods in order to identify when the impacts will take place. Return periods are commonly used to represent an estimate of the probability of a given event occurring within a given time frame.

We took the PMax24h for the following stations as a reference, as they are the ones that are closest to the assets studied[11] for the current period:

1. Cutting_A67_km175. Station 1124A, Villacarriedo (data from 1990 to 2021)
2. Cutting_N623_km117. Station 1154H, Torrelavega-Sierrapando (data from 1994 to 2021; missing 1999 and 2000)

The data were subjected to a statistical analysis (Gumbel distribution) for each of the stations in order to obtain the PMax24h for seven return periods, which were thus defined so that they could be linked to a risk classification scale. With these data, and using the inverse distance weighting (IDW) interpolation method provided by the QGIS Geographic Information System, we obtained a single PMax24h value per return period for the area of study in which the two assets analysed in the pilot study are located (see Table 3).

[11] This selection was made using the Thiessen polygon method, taking into account weather stations with datasets that were large enough to be representative.

Table 3 - Identification of the return periods for PMax24h by station using the Gumbel distribution. Reference value interpolated at the level of the territory in which the assets are located

Return Period (T)	Station 1154H	Station 1124A	Reference PMax24h (mm)
2	63.4147	78.3875	76.0497
5	77.3032	100.4764	96.8579
10	86.4987	115.1012	110.6351
25	98.1172	133.5796	128.0430
50	106.7364	147.2879	140.9564
100	115.2920	160.8950	153.7747
500	135.0627	192.3390	183.3961

Based on these data, we propose the following categories for the probability of the impact occurring (Table 4). The impact is defined as detachment of rocks and/or earth from the slope caused by the threat of PMax24h. For this exercise, we took into account the precipitation thresholds (as per the exposure matrix) above which the event occurs, and the return period of precipitation in the area of study (probability of the threat).

Table 4 - Probability matrix of the impact occurring due to PMax24h (mm/day). Current period, Cantabria pilot study

Probability	Very Low	Low	Medium	High	Very High
PMax24h (mm/day)	< 25	25-30	30-40	40-60	> 60

In this case, as the PMax24 value for the return period of two years is higher than the level of precipitation at which the impact analysed usually occurs, it was established that the probability of the impact occurring is very high (see Table 4).

The return periods serve to establish the thresholds, while the PMax24h values for the corresponding period and scenario, obtained from AdapteCCa, are used to ascertain whether these thresholds are exceeded in the specific area of study where the impact may occur.

For the future periods included in the climate change scenarios it is necessary to calculate the corresponding probability of the threat occurring, although this presents difficulties due to the uncertainty associated with the climate models. To determine the impacts for the future periods and scenarios, the same thresholds as for the current period will be used.

The risks posed to each asset by the effects of climate change will be determined based on the probability of the impact occurring (taking the thresholds established as a reference) and the severity of said impact.

6. CONCLUSIONS

Spain's geography is the product of a mosaic of microclimates and geomorphological and physiographic units. Consequently, depending on the specific details and needs regarding resolution capacity when calculating the risks posed to assets by climate change, we could propose many different scales for assessing the thresholds that determine the assets' exposure and the probability of the impact occurring.

Additionally, in urban and peri-urban areas, one of the factors that conditions territorial resilience is the extent to which the terrain is man-made. Land in urban areas has lost all of its capacity to provide ecosystem services to the surrounding environment and to the territory as a whole; instead, its characteristics are determined by the urban planning process and the detailed studies carried out in relation. The characteristics of the city's drainage systems, sanitation system, sewer system and green spaces condition the drainage capacity of its streets, squares and urban spaces. Road transport infrastructures require a detailed analysis in order to determine the thresholds that need to be defined for each type of asset and climate variable.

In the specific case of road assets affected by hydro-meteorological phenomena, more precise tools are needed to calculate the probability of the phenomena occurring and the level of impact. We are still some distance from knowing with a certain degree of accuracy the extent to which torrentiality occurs, including maximum precipitation in intervals of less than one day (duration of 1, 3, 6 and 12 hours), for Spain as a whole.

The information that is obtained from roads with regard to events and impacts associated with climate change must be organised at a nationwide level. This entails:

- Facilitating access to climate-related information.
- Compiling asset inventories containing information that is relevant in terms of assessing their sensitivity.
- Establishing a historical record of events that have taken place and their impacts, for the various modes of transport and for different assets.

Setting up this historical record is key, as with this information the competent territorial authorities would be able to establish specific management thresholds tailored to each type of asset, climate variable and territory.

For the specific case discussed in this article, in order to determine the thresholds we only took two assets into account, along with the corresponding data from the two nearest weather stations. Using a greater number of stations and assets would help to obtain more precise results, and provide a more accurate view of the current situation with regard to the risks to road infrastructure posed by climate change and the measures that could potentially be carried out in order to address its impacts.

Exploring and implementing this set of methodologies suppose large economic, social and environmental benefits for road agencies measurable by various methods such as CBA. This allows them to characterize road assets and services at high risk against current and future climate change effects. These benefits are observed when adaptation measures are implemented, among which early warning systems and emergency transportation operations response can be highlighted. To improve these systems and services, advanced methods for infrastructure monitoring should be implemented, such as remote sensing, drone surveillance, big data and data analytics.

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REFERENCES

1. PIARC (2016). International Climate Change Adaptation Framework for Road Infrastructure. PIARC
2. PIARC (2019a) Refinement of PIARC's International Climate Change Adaptation Framework for Road Infrastructure. PIARC
3. PIARC (2019b) Adaptation Methodologies and Strategies to Increase the Resilience of Roads to Climate Change. Case Study Approach. PIARC
4. IMT (2017) Panorama internacional de la adaptación de la infraestructura carretera ante el cambio climático. Instituto Mexicano del Transporte (IMT)
5. IMT (2019) Marco Metodológico para la Adaptación de la Infraestructura Carretera ante el Cambio Climático en México. Instituto Mexicano del Transporte (IMT)
6. IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.
7. European Commission (2021). Commission Notice: Technical guidance on the climate proofing of infrastructure in the period 2021-2027 (2021/C 373/01). C. (2021) 5430 final.
8. ISO (2019). ISO 14090:2019. Adaptation to climate change — Principles, requirements and guidelines. International Organization for Standardization (ISO)
9. TECNALIA (in press). Guía para el análisis de riesgos asociados al cambio climático. Fundación Biodiversidad junto a la Oficina Española de Cambio Climático (OECC), a través de una asistencia técnica de TECNALIA.
10. Grupo de Trabajo ATC-PIARC (2023). ¿De qué hablamos cuando hablamos de evaluación de la evolución del cambio climático en carreteras? Revista RUTAS. Nº 193. Asociación Técnica de Carreteras (ATC)
11. CEDEX (2021). Impacto del cambio climático en las precipitaciones máximas en España. Informe. Centro de Estudios y Experimentación de Obras Públicas (CEDEX).
12. National Academies of Sciences, Engineering, and Medicine (2020). Incorporating the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change Guidebook. Washington, DC: The National Academies Press
13. Alonso, M.L., Parra, L., Jiménez, F. & Crespo, L. (2022). Towards a More Resilient Spanish Road Network. PIARC. 16th World Winter Service and Road Resilience Congress. Calgary
14. CEDEX (2018). Secciones de la red estatal de infraestructuras de transporte terrestre potencialmente más expuestas por razón de la variabilidad y cambio climáticos. Informe Final. Centro de Estudios y Experimentación de Obras Públicas (CEDEX)
15. Collazos, F., Parra, L. & Alonso, M.L. (2022). Increased Resilience of Earthworks on State Roads in Northern Spain. Lessons Learned between 2011 and 2018. PIARC. 16th World Winter Service and Road Resilience Congress. Calgary