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Interim report

National climate change adaptation plan: transportation infrastructures and systems | Action 3

Analysis of the risks incurred by
extreme climate events on infrastructures,
systems and transport services | Collection of concepts

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Sétra

Interim report

National climate change adaptation plan: transportation infrastructures and systems, action 3

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systems and transport services – Collection of concepts

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Caution

In spite of the limits of this document, the DGITM wanted CEREMA to publish it, to provide players with the initial methodological references, even if they are only partial. Further to this publication, CEREMA will collect the feedback on this document and its update from potential users in view of European or international methodological documents in the same field.

In addition to the ongoing works, reactions and comments on the subject of this document will be used to produce a final document that will be presented in the form of a methodological guide.

This document does not represent the DGITM's views on the risk analysis and the vulnerability studies of transport infrastructures, systems and services, nor on the strategies and the measures to address this vulnerability.

Foreword

The fight against climate change is a national priority. The goal of COP21, also known as the 2015 Paris Climate Conference, is to reach an international agreement to keep global warming below 2°C.

Despite the efforts that have already been made to reduce greenhouse gas emissions, climate changes affecting temperature, the global water cycle, retreating snow and ice, the rise in the global average sea level and the modification of certain climate extremes will affect numerous sectors, including agriculture, forestry, tourism, fishing, biodiversity, urban and country planning, building and transport infrastructures.

In addition to mitigation efforts, it is necessary to prepare for this change. Otherwise the costs and the damage could be much higher than the cost of making the preparations. We must reduce our vulnerability to climate variations right away, if we are to avoid serious environmental, material, financial and human damage.

Adaptation to climate change, the essential complement to the mitigation actions already underway, has become a major issue that demands a nationwide effort. France adopted its national climate change adaptation plan (PNACC) in 2011.

The impacts of climate change on transport networks affect all modes of transport. Adaptation is essential, because transport networks and equipment are used for long periods of time. The PNACC identifies a number of measures. These measures are used to analyze the impact of climate change, to prevent the transport systems from becoming vulnerable and to prepare the improvement of the resistance and the resilience of existing and future infrastructures, so that people and goods can continue to be transported in safety.

This report relates to action 3 of the "transportation infrastructures and systems" section of the PNACC. The purpose of this report is to propose input for a method to analyze risks incurred by extreme climate events on transportation infrastructures, systems and services. This report is an initial collection of concepts intended to enrich case studies and exchanges of experiences.

Until now, the methods used to analyze the vulnerability of transport systems to climate change have not been extensively developed, even if the analyses of the risks of certain extreme climate hazards on certain parts of the network have been elaborated. This report proposes methodological input that is based on scientific research and case studies. In cooperation with the network operators, this report can be used to facilitate local studies of network vulnerability. New case studies have already been planned for 2015 and 2016.

This document brought together the central administration and the scientific and technical network of the ministry. This report will be made available to all the players involved: transport operators and infrastructure controllers, design offices and prime contracting local authorities, which are all invited to adopt these analysis tools and share their feedback, in order to enrich this initial collection of methodologies.

Directorate general for infrastructure, transport and the sea

May 2015

Introduction

The National Climate Change Adaptation Plan – PNACC – (MEDTL, 2011) was built on a collective and shared basis[1]. It was published on July 20, 2011, and was immediately applicable for five years. It applies to all public policies: health, urban planning, water, biodiversity, research, transport, etc.

The impacts of climate change on transport networks, irrespective of the mode of transport, could worsen in the coming century. These networks must be adapted, due to their importance to society and the economy, and the very long periods for which they remain in use.

A number of actions have been identified in the transportation infrastructures and systems section of the PNACC in order to achieve this. These measures will enable us to analyze the impact of climate change, to prevent the transport systems from becoming vulnerable and to prepare the improvement of the resistance and the resilience of existing and future infrastructures, so that people and goods can continue to be transported in safety. These actions are as follows:

- action 1: review and adapt the technical standards for the construction, maintenance and operation of transport networks (infrastructures and equipment used to deliver the service) in metropolitan France and overseas territories ;
- action 2: study the impact of climate change on transport demand and the consequences for reshaping transport provision ;
- action 3: define a harmonized methodology to diagnose the vulnerability of infrastructures and land, sea and air transport systems ;
- action 4: establish a statement of vulnerability for land, sea and air transport networks in metropolitan France and overseas territories and prepare appropriate and phased response strategies to local and global climate change issues.

At the request of the French directorate general for infrastructure, transport and the sea (DGITM) of the MEDDE, a work group was set up in 2011 tasked with the implementation of these actions. This group was made up of members of the scientific and technical group and the operators: CEREMA (DTer and DTec), CETU, IFRECOR, RFF, SNCF, STAC, STRMTG, VNF. The work group met several times to produce, amongst others, this collection of methodological concepts.

Before producing this document, the work group diagnosed the potential impacts of the expected climate change tendencies on:

- the reference materials applying to the design, maintenance and operation of transport infrastructures and systems ;
- existing transport infrastructures and systems.

Thoughts on this diagnosis were included in "National climate change adaptation plan: transportation infrastructures and systems, action 1; Potential impacts of climate change on transportation infrastructures and systems, on their design, maintenance and operation standards, and the need for detailed climate projections".

In order to perform this diagnostic, it was necessary to know the main climate changes described in the IPCC assessment reports[2] and the reports on the analysis supervised by Jean Jouzel (Peings, 2011, 2012; Planton, 2012). The following changes are taken into consideration in this report:

- gradual changes, such as the increase in the *mean daily temperature* index ;

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[1]Inter-ministerial report on the "evaluation of the cost of climate change" (2008, 2009), national Grenelle discussions (2010), regional discussions (2010), consultation of citizens (2010) and a final round table (2010).

[2]At the request of the DGITM, the diagnostic was based on the fourth IPCC assessment report (IPCC, 2007). The major differences between the fourth and fifth reports were also described (IPCC, 2013).

- changes in the occurrence of events, such as the increase in the *extreme values of daily precipitation* index.

Specialists have discussed and reported on the potential impacts of these changes in the climate on existing infrastructures. A number of infrastructures were covered: rail, maritime and river, highways, earthworks, constructions, mechanical lifts, guided transport systems and urban networks. Hundreds of design, maintenance and operations documents were reviewed. Any technical reference documents that could be impacted by climate change were listed, and then classified in three categories, in the order of priority of adaptation. Finally, the climate variables for which projections are necessary in order to adapt the technical reference documents were identified and analyzed.

This diagnostic will result in the adaptation of the technical doctrine and the quest for new practices or new materials. It will have to be completed by setting up a daily lookout by the departments that publish and use the technical reference materials for the construction, maintenance and operation of transport infrastructures and systems.

This diagnostic allowed us to prepare for the adaptation of transport infrastructures and systems to gradual changes and the occurrence of events. It is also possible to prepare the adaptation of infrastructures to extreme weather events, which cannot be easily anticipated or localized, in particular through risk analyses.

This document aims to provide some methodological input for the risk analyses, irrespective of the type of transport infrastructure or network. Extreme events are infrequent phenomena that have serious consequences (IPCC, 2012). In the realm of transport, these events can cause a network to shut down, interrupting service and threatening safety, security and the environment.

This document is a first partial contribution to action 3 of the "transportation infrastructures and systems" section of the PNACC. Essentially, it aims to present the concepts that are relevant to the risk analysis and to describe how they are related. Strictly speaking, it does not propose a risk analysis methodology.

In spite of the limits of this document, the DGITM wanted CEREMA to publish it, to provide players with the initial methodological references, even if they are only partial. Further to this publication, CEREMA will collect the feedback on this document and its update from potential users in view of European or international methodological documents in the same field.

In addition to the ongoing works, reactions and comments on the subject of this document will be used to produce a final document that will be presented in the form of a methodological guide.

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Chapter I

1 - General risk analysis methodology and main concepts

The purpose of this chapter is to present the main concepts and definitions, as well as the methodological framework, for the analysis of the risks incurred by transport infrastructures and systems in the face of extreme events.

To begin with, this chapter outlines the concepts that are of use in the proposed methodological approach. Risk analysis covers a broad field: natural risks, industrial risks, dependability, public safety, etc., and different language is used for each approach. The definitions that we propose do not call into question the definitions used within the specialized areas of risk analysis, but they will allow the reader to understand which concept corresponds to which definition in this document.

This chapter then presents the general methodological approach to risk analysis. There are two aspects to this approach: an analysis of the so-called "functional" criticality, i.e. the transport services affected by the climate hazards, and an analysis of the so-called "physical" criticality, i.e. the physical units that make up the transport network affected by the factors. This second part also addresses the connections between these two aspects and their respective possible degree of in-depth study. It also insists on the iterative nature of the links between these two aspects.

Thirdly, this chapter positions this method in the broader framework of strategies to protect or strengthen transport networks.

The following chapters then take a deeper look at the points presented in this first chapter. Finally, the annexes illustrate the general approach to risk analysis:

- studies that have already been completed and use all or part of the methodology presented in this collection ;
- summaries of risk studies that provided input for discussions on the development of the methodological framework presented in this document.

1.1 - Concepts and definitions

Figure 1 shows the terminology.

Schematically speaking, a **transport network** can be broken down into **individual systems**: constructions, stations, ports, airports, locks, pavements, quays, catenary systems, etc. These individual systems are, in turn, assemblies of various **components**.

Here, *climate hazards* refer to weather events that are exogenous to the transport systems, and to their consequences on the territories. They are characterized by an intensity, a spatial probability of occurrence and a probability of occurrence in time. In this report, only extreme climate hazards that cannot be easily anticipated and localized are taken into consideration. Examples include heat waves, floods, landslides, marine flooding, high winds, forest fires, etc.

They impact the individual transport systems, which are more or less **physically vulnerable**, depending on the characteristics of their components, their strength, their behavior, etc. This analysis, which cross-references climate hazards and the physical vulnerability of individual transport systems, is hereafter referred to as an analysis of **physical criticality**. It is made on a relatively microscopic scale.

The biggest **issues** at stake for a transport system lie in remaining functional. Schematically speaking, we can make the distinction between three types of functions: the essential transport functions, for example for the emergency services, the service and accessibility functions in certain zones, and the regular transport functions.

The failure or breakdown of an individual system, in particular due to an extreme climate hazard, impacts the level of service offered by the transport system and, therefore, the maintenance of the functions of the network, even in a degraded situation. This analysis, which links these issues to the **functional vulnerability** of transport networks, is referred to as the analysis of **functional criticality**. It is made on a relatively macroscopic scale.

Therefore, from a schematic perspective, the vulnerability of a transport system can be broken down into two levels:

- on a microscopic level: the physical vulnerability of its components, which depends on the physical characteristics of the components of the infrastructure, their strength, their behavior, etc.;
- on a macroscopic level: the functional vulnerability of the infrastructure network, which depends on the functional characteristics of the network, its capacity, whether it is meshed or not, etc.

The cross-referencing of climate hazards, the physical or functional vulnerability of the infrastructure and the issues, and the comparative analysis of the physical and functional criticality is referred to as risk analysis.

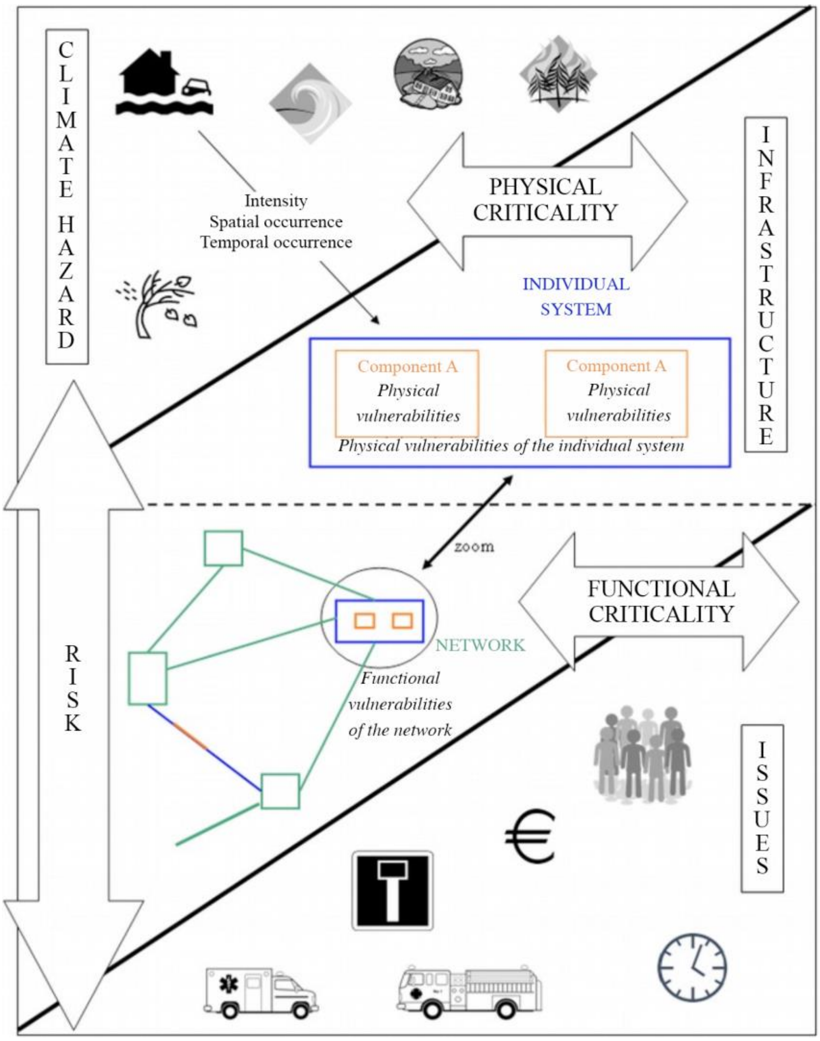

Figure 1: View of the concepts. Source: DGITM

1.2 - Methodological approach to risk analysis

Initially, the scope of the risk analysis should be defined according to the objectives. For example, the decision may be taken to conduct the analysis in a given territory, along a given route, on representative infrastructures, on the oldest infrastructures, etc. Then the risk analysis can go ahead. It is then necessary to compare the climate hazards, the physical and functional vulnerability of the infrastructures and the issues. The goal is to identify the parts of the network that are the most exposed to climate change hazards, in other words, the infrastructures that represent a high risk. This amounts to successively conducting the functional and physical criticality analyses.

From a methodological perspective, two approaches are possible:

- analyze the physical criticality first. In other words, determine the impact of each climate hazard on each of the individual systems (and their components) in the transport system, according to their characteristics and, in particular, their physical vulnerability, in order to determine which individual systems are liable to suffer serious damage. Then, examine how failures of the individual systems in the entire network could be combined, and proceed with an analysis of the functional criticality of the network. In other words, consider how the functionalities of the transport system are affected by the failure of one or more individual systems ;
- start with an analysis of the functional criticality. In other words, determine the individual systems in the network whose failure would be the most costly in terms of functionality, by comparing their importance with the characteristics of the transport network. Then, conduct a physical criticality analysis of the individual systems identified as being critical from a functional perspective, i.e., compare the climate hazards and the physical vulnerability of these individual systems in order to see whether the individual systems whose failure would be most costly are effectively liable to break down when exposed to different climate hazards.

In order to conduct these physical and functional criticality analyses, you should be in a position to:

- characterize the climate hazards (chapter 3). It is necessary to specify the expected climate changes, the type of climate hazards selected for the analysis and to identify their characteristics: intensity, spatial probability of occurrence and temporal probability of occurrence. Bibliographic and cartographic references are provided ;
- characterize the physical vulnerability of a transport network (chapter 4) when exposed to a climate hazard. The goal is to break down the studied network into individual systems and components, and then to assess the vulnerability of each of these individual systems and components to the various climate hazards, and to assess the global vulnerability of the systems ;
- characterize the performance of the transport network in the event of the degradation or failure of one of its individual systems (chapter 5). The goal is to describe the functionalities of the transport networks and to assess the impact of the loss of capacity or the failure of a segment of the network on these functionalities, in terms of quality and quantity.

The comparison of the physical and functional criticality analyses finally leads to the risk analysis (chapter 6). In practical terms, the functional and physical criticality analyses can be conducted simultaneously, in order to gradually refine the analyses on the cases where the level of risk is high. A distinction can be made between two levels of analysis:

- simplified analysis. In this case, the goal is to characterize the climate hazards, the physical and functional vulnerability of the infrastructures and the issues, on the basis of expert advice and feedback. The departments tasked with managing transport infrastructures usually include experts who are very familiar with the network or the individual infrastructures for which they are responsible. These experts can be consulted to voice an opinion on the physical or functional vulnerability of the transport networks. The same applies to experts in the climate hazards in a given territory. The experts can also call on a historical analysis of weather events in the past in order to build scenarios of the physical and functional impacts on the networks ;
- detailed analysis. This type of analysis uses advanced scientific and technical studies, using tools and models that are often complex, to characterize how individual infrastructures are impacted by climate hazards and how the performance of the transport network is impacted by climate hazards when one or more segments are degraded or fail.

The tools and models required for a detailed analysis may be expensive to develop and their use may be time-consuming. Therefore, it is generally quite difficult to use them for a comprehensive risk analysis of a given territory. It is thus preferable to proceed by successive iterations, while adapting the methods used (simplified or detailed analysis) at each level.

At each level, the distinction should be made between:

- infrastructures with low physical or functional criticality and, therefore, a low risk level ;
- infrastructures with moderate or high physical or functional criticality. The risk is potentially high for these infrastructures. Therefore, additional analyses should be conducted.

In some cases, simplified analyses are not sufficient to determine the level of physical or functional criticality. Obviously, in this case, detailed analyses should be conducted.

Figure 2 shows an example of an analysis method that starts with the analysis of the functional criticality.

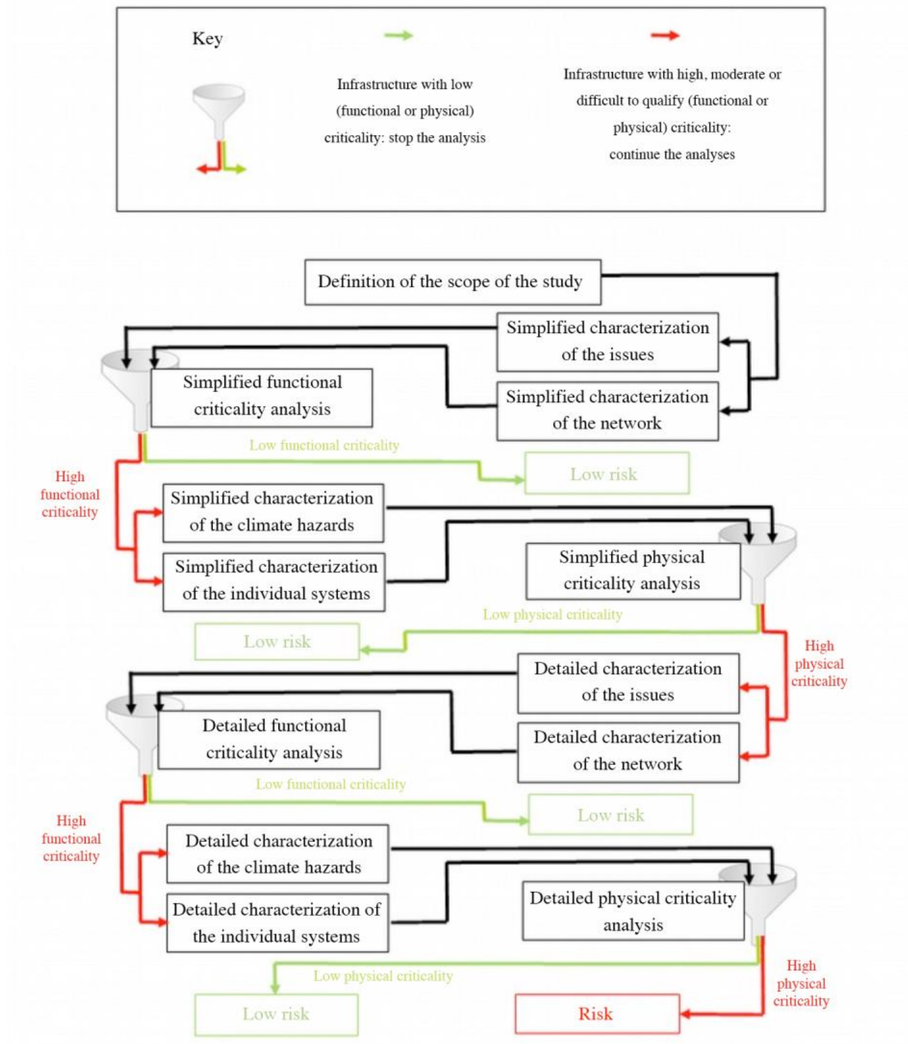

Figure 2: An example of a risk analysis method. Source: DGITM

1.3 - Connections with protective strategies and measures

Once the risk analysis has identified the high-risk systems and/or networks, it is possible to identify the "protective measures" to be taken in order to lower the level of risk.

Various protective measures exist. They can apply to the different components of the risk, to the climate hazards (e.g., the construction of dikes), to the infrastructure (e.g., strengthening structures, increasing the capacity of the networks, traffic management) or to the issues (e.g., relocation of certain activities, special services reinforced for emergency and care facilities). Moreover, the protective measures can be technical or organizational.

The costs and the benefits of taking a protective measure or a combination of protective measures for the transport network should then be assessed.

Chapter II

2 - Organizational framework of risk management

The potential impact of climate change on these infrastructures lies at the very heart of this document, which aims to propose a framework for risk management. This framework is intended to provide contracting authorities, controllers, operators, etc. with a diagnostic tool that will help them to consider climate change and its impacts in the planning, development, renewal, maintenance and management of their infrastructures. Therefore, this framework must:

- encourage good planning, development, renewal, maintenance and management practices, based on the risks incurred. These good practices must help the organizations to contribute to the definition of an efficient investment policy ;
- secure the long-term sustainability of the infrastructures through a better understanding of the vulnerability to climate change and the possibilities of adaptation.

It is essential to make sure that the risks posed by climate change can be determined precisely, and to specify the nature and the timetable of the responses to climate change, in order to make sure that the infrastructure networks are managed optimally by the contracting authorities and the operators.

2.1 - General framework

Interest in risk analysis and management theories has grown in recent years. These theories consist of managing risk by identifying and analyzing the risk and assessing the need to modify the risk by a specific process that meets predefined needs. Risk analysis also appears as a structured method to apply the principle of precaution and to make certain strategic choices. In this sense, its general framework is well adapted to the appreciation of the consequences of climate change on transport systems.

The standard NF-ISO-31000 (2010) clearly defines the organizational framework of risk management. The success of the risk management will largely depend on the efficiency of the institutional framework shown in Figure 3.

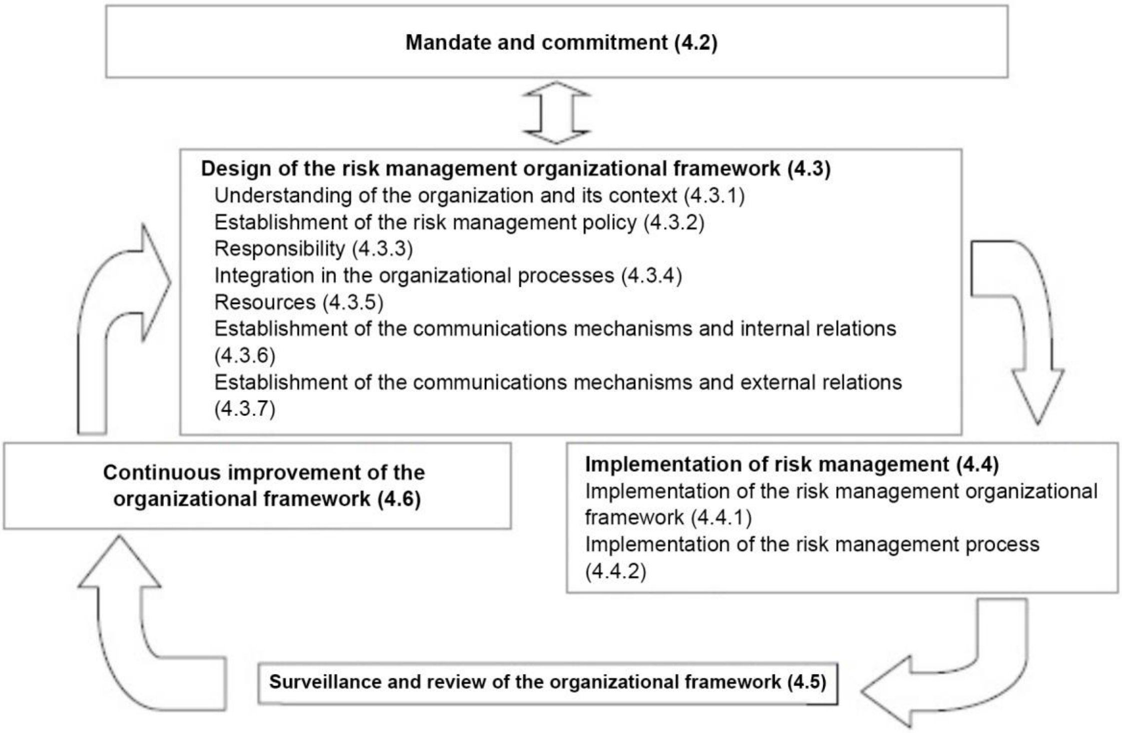

Figure 3: Organizational framework of risk management. Source: NF-ISO-31000 (2010)

This framework is not intended to prescribe a management system, but to help contracting authorities and operators to incorporate risk management in their global management system. The system must be adapted and applied to specific needs. The risk management process itself is described in Figure 4.

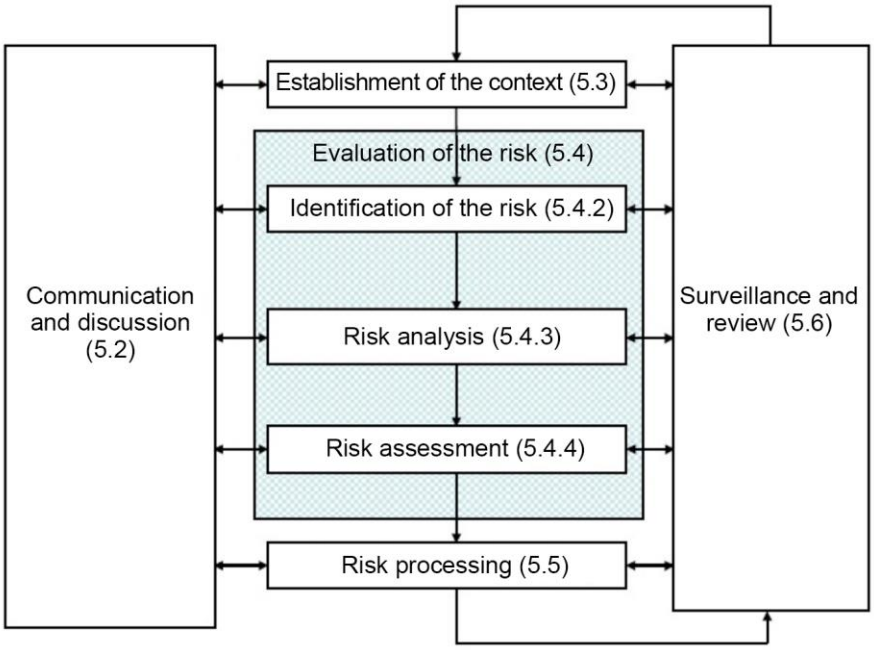

Figure 4: Risk management process. Source: NF-ISO-31000 (2010)

2.2 - Putting the approach into context

Firstly, the efficiency of a risk management-based approach will be determined by the strong and durable engagement of the contracting authority and the operator of the infrastructure. The risk management policy must be defined and management performance indicators must be applied that are coherent with the management strategy.

Secondly, the standard NF-ISO-31000 (2010) insists on the importance of assessing and understanding the internal and external context (environment), which influences the design of the organizational framework. The external context includes the social and cultural, political, legal, regulatory and financial environment, relations with external stakeholders, their perception of the risk, etc. The external context is multi-scale by nature. Therefore, special attention must be paid to the international context regarding the climate change adaptation policy, as well as to the local context (the region, the department, etc.). The internal context covers every aspect of the contracting authority or the operator that can influence the way in which risk is managed (culture, process, strategy, etc.). It is assumed that the scope of the study (international/national/local) has little influence on the internal context. Nevertheless, any specifics of the organization must be taken into consideration. Finally, the objectives, the strategies, the scope and the parameters of the operator's activities, to which the risk management process applies, must be defined. This includes the need to substantiate and specify the resources used to implement the process and to explicitly define responsibilities and the traceability of actions (Figure 4).

2.3 - The first steps of implementation

One of the first steps of a risk analysis consists of defining its objectives and choosing the territory to be studied. In particular, this step determines the choice of the resources to be deployed, the methodology of the analysis (chapter 6.1), etc.

As a general rule, when conducting a risk analysis, a working group is set up, in which the following are represented:

- transport specialists, such as associations, persons in charge of the operation, maintenance, development and technical strengthening of the networks ;
- climate specialists, capable of inputting information on past weather events and the expected changes in the climate ;
- specialists in the territory under study, with general knowledge of the territory: past climate hazards, local issues, the practical performance of the transport networks, etc. ;
- other specialists, according to the needs and the objectives of the risk analysis, and in particular, specialists in energy and communication networks. The deterioration of these networks can impact the operation of the transport networks.

The specialists in the work group will exchange frequently, in particular to decide on a common scale of values for the two climate variables that are necessary for the physical criticality analysis: the occurrence of climate hazards and the level of physical vulnerability of the studied networks. Similarly, the members of the work group must agree on a scale for the functional criticality.

Chapter III

3 - How to characterize the climate hazards

In order to assess the physical and functional criticality of a transport network, it is first necessary to know the climate hazards impacting the territory of the study, their expected evolution in terms of climate change and their potential impacts on the transport network. Not all the climate hazards need to be included in a risk analysis, but only those with the most significant impacts. Then, these climate hazards must be characterized and their probability of impacting the networks must be assessed and rated.

These steps are executed mainly by the climate experts, in dialog with the transport specialists.

3.1 - Understanding the climate hazards and their expected evolution with climate change

Numerous worldwide, national and regional studies have highlighted the physical impacts liable to affect transport due to the tendencies of climate hazards and the evolution of extreme events (URS, 2010; IPCC, 2012). These impacts obviously depend on the geographic area in question and the socio-economic context. Changes in the temperature, rainfall, wind, swell climate and water levels, and extreme events appear to represent the main impacts of climate change on the transport sector (CGEDD, 2013; EEA, 2012; FHWA, 2012).

The table below shows the main expected changes in these climatic variables and the climate hazards they cause (EEA, 2012; IPCC, 2007, 2013; Peings, 2011, 2012; Planton, 2012). Note that changes in biodiversity were also taken into consideration, because they can affect air transport.

Climate variable	Selected climate changes	
	Tendencies	Examples of extreme climate hazards
Temperature	Rise in mean temperatures in France	Increase in periods of drought by 2100 Rise in extreme temperatures Increase in the number of days of heat wave Heat wave Forest fires
Precipitation	Change in rainfall	Increase in the extreme values and the number of days of precipitation Drop in the number of days of snowfall Floods Landslides, collapsing, mudslides, rock falls, etc.
Wind	Changes in wind systems	Changes in violent wind systems Violent wind: storms, tornadoes, etc.
Swell climate and sea level	Rise in sea level (erosion and permanent submersion)	High sea waters (temporary submersion)
Groundwater levels	Change in groundwater levels Drop in river flows resulting from the increase in the number of days of heat wave	Change in groundwater levels Floods
Extreme events		Changes in the cyclonic system Cyclones
Biodiversity	Changes in biodiversity (increase in danger due to animals) Rise in the number of migratory birds due to the increase in temperature Increase in the proliferation of algae in watercourses due to the rise in the number of days of heat wave	

Table 1: Examples of climatic extremes and the corresponding climate hazards

This list of climate hazards is not exhaustive and could be completed in the course of the risk analysis. In this case, it is necessary to find the bibliographical references required to understand the climate change and the expected changes in the climatic variables. Some references can be found in chapter 3.5.

3.2 - Selecting the climate hazards

For practical reasons, it is not possible to select all the climate hazards listed in the preceding step (chapter 3.1). How are the climate hazards relevant to physical criticality chosen? (FHWA, 2012; STAC, 2013; VDOT (undated); WSDOT, 2011).

Initially, it is possible to select all the climate hazards presented in chapter 3.1 and their potential consequences on a territory. Examples of consequences include changes in the population of certain species of migratory birds due to the rise in mean temperatures, or the increase in the proliferation of algae in watercourses due to the rise in the number of days of heat wave, the drop in flow rates in rivers due to the rise in the number of days of heat wave, etc.

The list of climate hazards to be studied is then modified:

- according to the objectives of the risk analysis. Some risk analyses may choose to concentrate on one climate hazard, or on all the climate hazards liable to occur in a given territory ;
- according to the scope of the risk analysis: the territory (21), the selected timescale, etc.

Finally, the experts can call on their knowledge of events in the past that impacted the infrastructures to make the list of climate hazards to be studied even more precise. Therefore, at this stage, it is already possible to select the climate hazards liable to have a significant impact on these systems, in order to have a more "optimal" vision of problems that may arise due to climate change. These climate hazards that could have an impact are chosen in an iterative manner, in parallel with the breakdown of the networks into systems and components. A breakdown methodology is proposed in chapter 4.2. This methodology produces a precise description of the networks and the component parts of the description can be used to form a matrix (chapter 4). This matrix can be used to verify the impact of each climate hazard on the networks.

It is interesting to begin by verifying the possible impact of the listed climate hazards on the networks at a relatively low level of detail. To do this, it is possible to take the list of climate hazards (chapter 3.1) and to verify their potential impacts on the large categories of individual systems that make up the networks (chapter 4.3). The result can also be presented in the form of a table (Table 2).

		Climate hazards that could be considered		
		Climate hazard no.1	Climate hazard no.2	...
Networks studied	Family no.1 of individual systems	Impact of climate hazard no.1 on family no.1 of individual systems?	Impact of climate hazard no.2 on family no.1 of individual systems?	…
	Family no.2 of individual systems	Impact of climate hazard no.1 on family no.2 of individual systems?	…	
	…	…		

Table 2: Table used to verify the potential impacts of the climate hazards on the networks at a low level of detail

As and when the networks are broken down (chapter 4.2), it is possible to specify the potential impact of the climate hazards on the networks (chapter 4.3). At this point, it is possible to select new climate hazards or to decide not to retain those that were selected previously. The result is again presented in the form of a table (Table 3).

			Climate hazards that could be considered		
			Climate hazard no.1	Climate hazard no.2	...
Networks studied	Individual system no.1	Component no.1	Impact of climate hazard no.1 on component no.1?	Impact of climate hazard no.2 on component no.1?	…
		Component no.2	Impact of climate hazard no.1 on component no.2?	…	
		…	…		
	Individual system no.2	Component no.1			
		Component no.2			
		…			
	…				

Table 3: Table used to verify the potential impacts of the climate hazards on the networks in detail

3.3 - Characterizing the selected climate hazards

Once the climate hazards that could have a significant impact on the networks have been identified, it is necessary to characterize them in the present and the future and, therefore, to define climatic scenarios. In this way, their probability of occurrence, which is essential for the analysis of physical criticality, can be assessed.

In risk management, a climate hazard is characterized by:

- *an intensity*. The intensity expresses the quantification of an event. It can be measured or estimated. In practice, thresholds of the classes of weather phenomena are used – rain, frost, snow, wind, heat, etc. (IPCC, 2007, 2013; Peings, 2011, 2012; Planton, 2012) ;
- *a spatial occurrence: predisposition and extension*. Spatial occurrence is conditioned by factors of predisposition or susceptibility, for example geological. The spatial extension of a climate hazard can be highly variable, from very local (a few km²), to national, and very difficult to estimate. For example, this is the case of avalanches or landslides. Furthermore, the spatial occurrence of the climate hazard should be distinguished from the impacted territory. Very localized precipitation can cause widespread flooding ;
- *the temporal occurrence of the climate hazard: instant and duration*. The temporal occurrence can be estimated qualitatively (negligible, low, high) or quantitatively, by recurrence intervals (decennial to centennial, for example). The duration of the

phenomenon must also be taken into consideration. The duration can vary between a matter of hours, days, weeks or months.

It could be helpful to define:

- pessimistic, optimistic and middle-of-the-road climate change scenarios, in order to take the uncertainties of climate projections into consideration ;
- or scenarios on different timescales, for example up to 2030, 2050, or even 2100. In this way, the expected changes in the climate hazards due to climate change can be taken into account. The intensity and the duration of each climate hazard can rise or fall, or the recurrence interval can change, as a bi-decennial event becomes decennial, etc. Defining scenarios on different timescales also allows short- and long-term adaptation strategies to be developed.

In this case, the climate hazards are characterized several times. A physical criticality analysis, and therefore a risk analysis, will be associated with one scenario. Defining scenarios also allows potential combinations of climate hazards to be taken into consideration. For example, it is possible to define a scenario in which the intensity of extreme rain events increases, and associating it with more frequent flooding.

The intensity, the spatial probability of occurrence and the temporal probability of occurrence must be entered in the table, whenever possible, for each climate hazard and for each scenario. Temporal occurrence and/or intensity are decisive in the rating of the climate hazard, while spatial occurrence is considered before the physical criticality analysis.

3.4 - Rating the climate hazards

Once the climate hazards have been characterized, the climate and transport network experts assess the importance of their impacts in the definition of a prevention and adaptation strategy. Therefore, a suitable scale must be defined to rate the temporal probability of occurrence of the climate hazard and/or its intensity. In practice, this consists of producing definitions for each level of the scale and collectively finding answers to questions such as "What is a high/moderate/low occurrence/intensity of a climate hazard?" "Once every 1, 2 or 10 years?" etc.

The table below shows an example of a scale with four levels applying to temporal occurrence (Table 4). Other examples can be found in the bibliography.

Class	Category Frequency	Description	Probability of occurrence by hours of service
4	Likely	The event is liable to occur several times in the lifespan of the system.	$> 10^{-5}$
3	Rare	The event is liable to occur once in the lifespan of the system.	10^{-5}-10^{-7}
2	Unlikely	The event is highly unlikely, but the risk of its occurrence in the lifespan of the system is not zero.	10^{-7}-10^{-9}
1	Extremely unlikely	The event is so unlikely that the risk of its occurrence in the lifespan of the system is considered to be zero.	$< 10^{-9}$

Table 4: Example of a four-level scale used to characterize the probability of the selected weather events as part of a given risk analysis

At this point, in order to prepare the "climate hazards x physical vulnerability" cross-referencing exercise (54), it is advisable to enter the following information in a table:

- the selected climate hazards ;
- their characteristics, described using the method proposed in 26 ;
- their rating according to a scale defined using the method described above.

The result can be presented in the form of a table (Table 5).

Selected climate hazards		
Climate hazard no.1	Climate hazard no.2	...
Characteristics	Characteristics	...
Rating given to climate hazard no.1	Rating given to climate hazard no.2	...

Table 5: Table summarizing the characterization and the ratings of the selected climate hazards

3.5 - Bibliographic and cartographic references required to characterize the climate hazards

It is helpful to have access to databases on the expected changes in the climate and statistics of weather events in the past. This enables us to identify the climate hazards with potential impacts, their expected evolution as part of climate change, and to choose, and then characterize, those that are necessary for the risk analysis. The following paragraphs present some databases and their possible uses in risk analyses.

3.5.1 - Understanding climate change

Climate change:

"A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use."

(IPCC, 2012)[3]

The members of the Intergovernmental Panel on Climate Change (IPCC) are unanimous: "Warming of the climate system is unequivocal" (IPCC, 2007). The panel's conclusions, exposed in its 5th report published in 2013, are formal: climate change is in progress and its effects will have consequences on the climate in the short and medium terms. Previous works by the IPCC (the 4th report – IPCC, 2007) were validated by the Academy of Sciences in October 2010, and in particular its work on the reality of global warming, on the primary responsibility of anthropic emissions for this phenomenon and on the importance of modeling the future climate. Therefore, the following chapters are based on the scenarios in the 4th report.

[3]In this report, the notion of an extreme weather event corresponds to the definition proposed by the Intergovernmental Panel on Climate Change (IPCC) in its *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) (IPCC, 2012).

General principle of climate modeling
Climate models are very complex mathematical tools that are capable of projecting changes in the elements that make up the climate system. The principle of climate models is based on the mathematical representation, using a set of equations, of the physical phenomena that determine the evolution of the atmosphere and oceans. These equations are applied to a calculation matrix, with meshes of different resolutions, that covers the surface of the globe, the thickness of the atmosphere and the depth of the oceans. The resolution of these equations at the different points of the mesh and the comparison between these results and observed results improves the equations and the configuration used. Changes in the concentration of greenhouse gases in the atmosphere are one of the necessary inputs for these climate models.

Climate scenarios
The IPCC proposed different change scenarios for anthropic emissions and concentrations in greenhouse gases and particles for the 21st century.

- Scenario A1 describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. It also describes convergence among regions, particularly in terms of per capita income. In scenario A1, technological development respects a balance across all energy sources ;
- Scenario A2 describes a very heterogeneous world, with economic development that is primarily regionally oriented, a continuously increasing global population and technological change that is slower than in the other storylines ;
- Scenario B1 describes a convergent world with a global population that peaks in mid-century and declines thereafter, as in the A1 storyline. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity ;
- Scenario B2 describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. The world's population continues to grow, but at a lower rate than in scenario A2. Technological development is slower and more diverse than in scenarios B1 and A1.

It should be understood that a risk analysis can be based on other scenarios, in view of the rapid progress of the studies and forecasts on the subject.

Climate models
What does the next century have in store for us? It is thought that changes in temperatures, precipitation, extreme events and water levels will constitute the main effects of climate change on the transport sector. For a better understanding of what could happen in the close or more distant future, the IPCC's scenarios were used in climate models covering France, as part of an expert analysis supervised by Jean Jouzel, Vice-Chair of IPCC Working Group 1 "The Physical Science Basis", in January 2011.

Climate change in France was simulated using French regional climate models, such as, for example: ARPEGE-Climat and LMDz, respectively developed by CNRM-Météo-France (the French national meteorological research center) and the IPSL (Institut Pierre-Simon Laplace):

- the ARPEGE-Climat model used by Météo-France is derived from the operational short-term forecasting model ;
- the LMDz model is also a variable mesh general circulation model ;
- the ALADIN-Climat model used by Météo-France is derived from the ALADIN operational short-term forecasting model ;
- the MAR model, like ALADIN-Climat, is a model covering a limited-area domain ;

- finally, the ANR SCAMPEI[4] (Piazza et al., 2012) project provides a more precise answer to the question of climate change in mountainous regions in metropolitan France. It is partly based on simulation models derived from the analysis supervised by Jean Jouzel. Extreme phenomena, snow cover and uncertainties are modeled with a finer mesh (8 km) in order to take account of the topographical complexity.

On a worldwide scale, the IPCC used 23 AOGCM type models (the most complex) to produce these reports and their climate scenarios.

Uncertainties inherent in the modeling and the science of the climate

On the basis of complex models and various hypothetical socio-economic forecasts, uncertainties still exist in the predictions of the future climate. They are linked to:

- the natural variability of the climate ;
- the greenhouse gas emissions scenarios, and in particular emissions of greenhouse gases resulting from the policies to reduce greenhouse gas emissions that our societies will adopt and to the modeling of greenhouse gas emissions ;
- the capacity of climate models to reproduce the workings of the climate.

The IPPC's models come from various research centers. They are distinct in terms of their parameterization. These differences are mainly the result of the documented choices made by the scientists who designed them. Using these models produces more robust results, because they are less dependent on the choices of parameters. This method reduces uncertainty and specifies the margins.

In France, the national climate change adaptation plan (PNACC) is based on the results presented in the reports published in the analysis supervised by Jean Jouzel in January 2011 and February 2012 (Peings, 2011, 2012; Planton, 2012). In order to take the uncertainties of climate modeling and the emission scenarios used into consideration, the report published in January 2011 was based on two models – ARPEGE-Climat and LMDz – and two scenarios: scenario A2, which is considered to be rather pessimistic, and scenario B2, which is rather optimistic. The report published in February 2012 was based on:

- three climate models, each for three 30-year periods: 1961-1990 as the reference period, 2021-2050 for the near future and 2071-2100 for the end of the century ;
- scenarios A2 and B2 ;
- simulations based on scenario A1B of the concentration of greenhouse gases and aerosol gases.

All the simulations are available in the DRIAS database[5] (French regional climate change scenarios for impact and adaptation of our society and environment).

Climate projections

Data on worldwide climate projections from numerous models is available in the various IPCC reports. There are several reports on climate projections on a national and regional scale and on the ongoing scientific work on this subject. The reports written under the expert supervision of Jean Jouzel (Peings et al, 2012) were produced in response to a request from the French Ministry of the Ecology, Sustainable Development, Transport and Housing, which tasked him with organizing the projections produced by meteorologists[6] required to produce climate projections.

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[4]http://www.cnrm.meteo.fr/scampei

[5]http://www.drias-climat.fr/

[6]At the Météo-France Meteorological Research Center and Institut Pierre-Simon Laplace

The results of the climate projections available at the time of writing of this interim report are taken from the 4th IPCC assessment report and the reports published by the analysis supervised by Jean Jouzel in January 2011 and February 2012. The main categories of climate variables studied are temperature, precipitation, groundwater levels, wind, extreme weather events, sea level, swell climate and biodiversity in metropolitan France and French overseas territories.

3.5.2 - Defining the climate scenarios

Climate projection databases

The question of adaptation to climate change requires highly localized data on differing timescales. A part of this data is currently produced by climate research laboratories in the form of climate scenarios. In view of their degree of technical complexity, they can only be accessed and used by socio-economic players with some difficulty. It is essential to make them more accessible. The *Drias les futurs du climat* (<http://www.drias-climat.fr/>) portal offers a response to this need by allowing all the players involved in the adaptation to climate change (local authorities, State departments, design offices, companies, etc.) to easily consult and obtain the data and products produced by digital climate simulation models. The creation of the *Drias les futurs du climat* portal is a major cross-sectoral development that is part of the French national climate change adaptation plan. Météo-France will continue to enrich the portal with the latest research work in the French and international scientific communities. *Drias les futurs du climat* offers open and free access to the latest advances in modeling and climate services. The information is data on a regional scale from the most recent climate projections produced by members of the climate research community in France (CERFACS, CNRM, IPSL), and in particular the SCAMPEI project. The parameters and indicators are represented with different resolutions for the whole of metropolitan France.

The portal is organized in three sections:

- a Discovery section, containing interactive maps showing different climatic indicators. This space offers an immediate analysis and allows for a clear understanding of the data sets and the products that can be accessed in the portal ;
- a section for Access to the data and products. After identifying themselves, users can order and download regional climate projections in digital format (raw data and data corrected with observations). This space is mainly intended for informed users who, for example, use this data in impact studies ;
- a Support section, which contains explanatory texts, an FAQ, a support center and the information required to make proper use of the services on offer from the *Drias les futurs du climat* portal.

Other information sources can also be used, such as the Météo France site[7], which contains data on local rainfall and temperatures, and also provides access to their projections.

Finally, various documents have been published that summarize the data on the expected changes in the climate on a more local scale. One example on a regional level is SCRAE (*Schémas Régionaux du Climat, de l'Air et de l'Énergie* – regional climate-air-energy plans), which provides a view of the expected changes in the climate on a regional scale and for different timescales. It also analyzes the vulnerability of the region in question to the effects of climate change. These documents are assessed and can be revised. The decree published in the French Official Journal (Journal Officiel) on June 18, 2011, defines their content and how they are produced (articles R, 222-1 to R, 222-7 of the French environmental code).

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[7] <www.meteofrance.com/climat/france>

Feedback and climatic analogies

When we look to the future to define climate scenarios as part of a risk analysis, it can be difficult to find quantified references on changes in climate hazards. For example, what would be the impact of a rise in the intensity of rain on the flow rates in navigable waterways? In order to overcome this difficulty, we must "transpose" current events into the future, using a database of current events, in particular. In the example above, the following information would be necessary: "for an extreme rainfall event of current intensity Y, the corresponding flow rate is X". So if we forecast a two-fold rise in the intensity of rainfall in 2100 compared with today, we can:

- either state that the corresponding flow rate is 2x, according to expert advice, with, for example, possibilities of slides ;
- or use a calculation model to estimate this flow rate.

It is also possible to use another basis :

- a feedback lookout: extreme events, the 2003 heat wave, known storms, etc.;
- and/or analogies with territories already exposed to these climate conditions.

Chapter IV

4 - How to characterize the physical vulnerability of a transport network

Physical criticality is determined by the impact of each of the selected climate hazards on each of the individual transport systems (and their components), according to their characteristics and, in particular, their physical vulnerability. This process determines the individual systems that are liable to suffer serious damage.

Physical criticality is analyzed in two stages: first, the main families of systems in the networks are analyzed on a global scale, then each system and its components are analyzed in more detail. Good knowledge of the networks is necessary in order to break them down into individual systems and components, and to define their characteristics and physical vulnerabilities in detail. The characterization of the networks and their vulnerability to the climate hazards is gradually refined as the risk analysis progresses, in an iterative manner. The level of detail depends on the expected objectives, which may apply to a given network (optimization of interventions on the network, anticipation of major capital outlay, re-assessment of operational measures, application of emergency instructions to protect the safety of users, etc.) or on the prioritization of the interventions on the infrastructures.

4.1 - Notions of physical vulnerability and physical criticality

The vulnerability factors are introduced as elements that heighten the risk (absence of alerts, effects on the site, etc.) or as factors of the sensitivity of the infrastructure to weather events (blocked nozzles, deteriorated structures, performance of the water evacuation system, etc.). Vulnerability is a concept that is widely used in several fields of research, but its definition is often ambiguous and sometimes leads to misunderstandings. In this report, we have chosen to make the distinction between functional vulnerability and physical vulnerability, which is defined as the sensitivity of a network to a particular climate hazard, or the amplitude of the damage caused by the occurrence of this climate hazard. Therefore, intrinsic physical vulnerability does not exist, but only a physical vulnerability to each of the climate hazards in question. Physical vulnerability depends on the components that are exposed, their strength, their behavior, etc.

Therefore, a system can be vulnerable to one climate hazard, but robust and resilient to others. Consequently, the distinction needs to be made between the concepts of robustness and resilience. Robustness is the capacity of a system to operate in a degraded situation when faced with a given climate hazard, which provokes damage (malfunctions). Resilience is the capacity of a system to fully or partially restore its functionality following the occurrence of a climate hazard.

The notion of physical criticality must be related to physical vulnerability and can be seen as a characteristic of a component or of an assembly of components in a system. Here again, several definitions are used in the scientific literature. One interpretation states that the critical systems and components are those that are essential to the operation of the transport network. Physical criticality can be judged by the amplitude of the climate hazard on the one hand, and by the vulnerability of the system to this climate hazard on the other, or by the combination of these two notions.

The notion of vulnerability is particularly important. It was introduced into scientific and technical works in response to criticism that risk analyses are often overly "climate hazard-centric" and do not take into consideration the capacity of a system to resist when exposed to climate hazards.

4.2 - Breakdown of the transport network into individual transport systems and components

The individual systems that make up a transport network are not all sensitive to the same climate hazards. It is necessary to break down the transport system into individual systems, and then to break down each system into components. This breakdown allows the vulnerability of each part of the network to be characterized as part of the physical criticality analysis.

An iterative process is recommended to limit the breakdown to the systems or components most sensitive to each climate hazard. For example, thorough knowledge of the highways drainage system would be useful for the "heavy rain" climate hazard, but of little use for the "heat wave" climate hazard. The more detailed the description of the network, the longer and more complex the analysis. Therefore, it is necessary to adapt the level of detail to the objectives of the analysis (chapter 2.3). It is also preferable to adapt the level of detail to the available data for the purposes of the analyses. This is why it is usually advisable to start by breaking down the transport network into large families of individual systems, rather than very precisely detailing all the components right from the start of the analysis. This is especially true when large networks, such as networks that cover extensive territories, are being analyzed.

Once the breakdown has been completed, it is necessary to describe the components and systems. Depending on the infrastructure and the composition of the group of experts, this description could take the internal mesh of the public transport network and the entire multimodal transport system into consideration. It may also be useful to document the issues facing the parts of the network in this description. This exercise is documented in chapter 4.

This work should be entered in a table in order to cross-reference the "characteristics of the climate hazards x the physical vulnerability of the networks", in other words, the physical criticality analysis. An example of a breakdown table (Table 6) is shown below. This example is from the COUNTERACT[8] project and shows the breakdown of an urban public transport network. The level of detail is very high and particularly well adapted to localized urban systems, but it would not be recommended for a broader study of an entire conurbation.

[8]COUNTERACT is a European project in which the risk mapping method presented in this document was tested in the analysis of the vulnerabilities of transport infrastructures to the risk of terrorist attacks.

Target category			
Category	Sub-category 1	Place/Object	Description
	Sub-category 2	...	...
Subway	Subway station at Place de la République	Pedestrian access	Escalators 1-4
			Secondary entrances
			Main entrances
		Vehicle access	
	Subway stations (all)	Line 2	Access to the platform
	Control room	Control room 1	
		Control room 2	
Bus	Bus network	Stops	Stops (all)
			Stops on line 10
		Rolling stock	
		Depot	
	…	…	…

Table 6: Result of the breakdown of a transport network. Example of a matrix used in the COUNTERACT project (COUNTERACT Consortium)

In this example, the category corresponds to the "network under study". The subcategories, or "systems", are broken down into place/object, or "components".

The approach described above can, of course, be transposed to other types of networks or systems. In this way, a network can be broken down into large families of systems, for example constructions (bridges, tunnels, etc.), stations, sections of rail track, ports, sections of rivers, airports, sections of roads, etc. Each of these systems can then be broken down into components. For example, a rail network can be broken down into the rail track, the rails, overhead lines, signaling gear, constructions, etc.

4.3 - Verifying the vulnerability of a network to a climate hazard

The table showing the breakdown of the network can be used to identify the network's main systems and/or components. The next step consists of checking whether these systems and/or components are really exposed. To this end, it is necessary to take the impacts that can cause the climate hazards on the networks into consideration, on the basis of the factors of vulnerability of its components and systems.

4.3.1 - Determining the network's physical vulnerability factors

This step requires a list of the physical vulnerability factors. The priority factors to be considered in the analysis include (the RIMAROCC project, 2010; FHWA, 2012):

- the age of the infrastructure, from a few years to more than 100 years ;
- the scheduled lifespan and the condition of the system relative to this lifespan ;
- the design rules: absent, old or modern ;
- the materials used ;
- the existing inspection and maintenance procedures, ranging from no actions at all, to detailed and systematic inspections after every exceptional event ;
- feedback on the behavior of the network in the face of climate hazards ;
- the elevation of the infrastructure relative to sea level or a watercourse ;
- etc.

Some of these factors are more difficult to assess than others, and less differentiating.

Depending on the level of detail of the analysis, it may be necessary to complete the list of vulnerability factors.

4.3.2 - Verifying the vulnerability of a component to a climate hazard

Once the list of the physical vulnerability factors of the network's systems and/or components is known, their vulnerability to a climate hazard must be verified. In this step, the network experts and the other experts in the working group can call on the definition of the impact scenarios of the climate hazards. These scenarios must allow the type of vulnerability of the component to a climate hazard to be described qualitatively, using the list of vulnerability factors, or quantitatively, using software. It may also be helpful to check whether the vulnerability of a component to a climate hazard can have consequences on the vulnerability of the entire system, or even the entire network: "Can the vulnerability of component X have any consequences on the vulnerability of another component?" For example:

- component no.1 of the system is vulnerable to climate hazard no.1 ;
- component no.2 of the system is not vulnerable to climate hazard no.1, but the deterioration of component no.1 is liable to bring about its deterioration.

In this case, the vulnerability of component no.2 must be reassessed in relation to the vulnerability of component no.1. For example, it is possible to define that:

- the two components are equally vulnerable to the climate hazard ;
- or, if a severe deterioration of component no.1 brings about a slight deterioration of component no.2, that component no.1 is very vulnerable to climate hazard no.1 and component no.2 is moderately vulnerable to climate hazard no.1.

The definition of these impact scenarios can also call on:

- scenarios of socio-economic changes (VDOT, undated). Economic developments can impact the state of upkeep of the systems ;
- development scenarios of the territories, which allow changes in urban development, etc. to be taken into consideration, and, therefore, changes in places where access is an issue ;
- other scenarios, including changes in government policy on the management of existing infrastructure assets (VDOT, undated). Similarly, broader impacts on the territory may also be projected, in order to take any induced effects into consideration. For example, a climate hazard that impacts the energy transport networks can indirectly impact rail traffic.

The assessments of vulnerability can then be documented by combining the breakdown table of the climate hazards and of the characterization of the climate hazards (Table 5, possibly without the ratings given to the climate hazards) in a single table (Table 7).

			Climate hazards that could be considered		
			Climate hazard no.1	Climate hazard no.2	…
			Characteristics	Characteristics	Characteristics
Networks studied	Individual system no.1	Component no.1	How and why is component no.1 vulnerable to climate hazard no.1?	How and why is component no.1 vulnerable to climate hazard no.2?	
		Component no.2	How and why is component no.2 vulnerable to climate hazard no.1?	…	
		…			
	Individual system no.2	Component no.1			
		Component no.2			
		…			
	…	…			

Table 7: Table used to verify the potential vulnerability of the systems and components of a network in detail

4.3.3 - Rating the physical vulnerability of the network

Once the vulnerability table has been completed (Table 7), a vulnerability rating must be given to each of the systems and components in the network. A vulnerability scale must be defined in order to do this. Like for the definition of the scale of climate hazards (chapter 3.4), the definitions must be established for each level of the scale.

At this stage, the result can be presented in the form of a table, as shown below (Table 8).

Networks studied	System no.1	Component no.1	Vulnerability rating of component no.1 (system no.1)
		Component no.2	Vulnerability rating of component no.2 (system no.1)
		…	…
	System no.2	Component no.1	…
		Component no.2	…
		…	…
	…	…	…

Table 8: Table of the physical vulnerability ratings

4.3.4 - Resources to assess the vulnerability of a network to a climate hazard

Various methods can be used to compile and weight a list of vulnerability factors.

Feedback

The experts can be consulted:

- in meetings. These meetings can be attended by experts in a given type of infrastructure, or experts in a particular segment (WSDOT, 2011). Deciding on the scale of vulnerability in a collegiate manner in a meeting produces a harmonized scale for all the experts, who then have to agree on the definitions of the levels of vulnerability ;
- by questioning the experts individually, using questionnaires or in interviews (STAC, 2013).

In this way, they can state which infrastructures are the most vulnerable, on the basis of their own knowledge and experience.

Databases and documentation

It is also possible to assess the vulnerability of an infrastructure using:

- databases: IQOA (images of the quality of constructions) and IQRN (images of the quality of the national highways network) provide indicators of the conditions of constructions and roads ;
- studies: for example, the CEREMA guide to risk management applied to constructions defines a number of physical vulnerability factors (Sétra, 2013) ;
- field investigations ;
- statistics or historical data, for example from the verifications and inspections of infrastructures by the operators ;

- modeling: for example, there are models of the behavior of infrastructures according to different loads (wind, etc.) ;
- etc.

Nevertheless, it may prove difficult to access this type of information, which usually comes from a range of different sources: specific databases, feedback from the highways operators, experts, etc.

Chapter V

5 - How to assess the functional vulnerability of a transport network

The purpose of a transport network is to allow passengers to travel in comfort, or to transport goods. Generally speaking, the performance of a transport network covers:

- connectivity: does the network allow for travel from one place to another ?
- quality of service: under which conditions of speed, comfort, safety, reliability, etc. does the network allow users to travel ?
- capacity: how many users can the network convey simultaneously ? The notions of quality of service and capacity are closely linked. If we want to transport more people or goods at the same time in the same place, inferior quality would result in wasted time, inferior reliability, congestion, queues, etc. ;
- costs: a transport network incurs construction, maintenance and operating costs that are reflected in the prices paid by the users, or in the contribution made by taxpayers.

Each one of the systems (highways, bridges, tunnels, rail tracks, stations, etc.) making up a network contributes to the performance of that network. If one of these systems is unavailable, then the network will be less efficient, and this will have an impact on one or more of the variables mentioned above.

The purpose of the functional criticality analysis is to identify the impact of failures on the performance of the network. This is part of the input that can be used to establish the priorities of the means of protection and the solutions to be deployed.

These failures, which may be caused by extreme weather events, can occur in isolation (a road is washed away by a landslide, but the rest of the network is unaffected) or at the same time (flooding blocks several roads and railroad lines in the same sector). In both cases, such events may only have a minor effect in terms of the functionality of the network (the affected routes are not very busy and alternatives are available; users are still able to travel under conditions that are almost normal) or they may have a very serious impact (travel becomes much more difficult, or even impossible).

These impacts are measured according to the scale of the variables mentioned earlier. In order to know whether a system or a set of systems is essential to the operation of the network, it is necessary to identify what it is used for, why, and how the users can adapt if it becomes unavailable. This is the goal of the functional criticality analysis.

This exercise takes place in three steps. The first step details the functions of the transport network and defines the notion of performance for each of these functions. The second presents the principles of the functional criticality analysis. In the final step, examples of the methods that can concretely be used are presented.

5.1 - The functions of a transport network

From the perspective of the functional criticality analysis, three main functional categories can be distinguished:

- **essential transport functions:** this category includes movements that must be possible at all times and at all cost, especially if an extreme weather event occurs. These movements include access for rescue services, medical services, firefighters, the police, the evacuation of persons (by their own means or otherwise), the transportation of basic necessities, military transport, etc. This is essentially a question of connectivity. It must be possible to reach anywhere from anywhere, given that the solutions providing this connectivity may include barring access to the transport networks to other users, the design and use of special vehicles, the use of other modes of transport, etc. ;

- **service or accessibility functions**: this category includes movements involving essential services, such as access to food, health services, etc. Substitutes are available for these movements. For example, if the food store becomes inaccessible for the people living in a given place, but another food store is available, then there is no particular problem. On the other hand, if all the stores become inaccessible, then the consequences can quickly becomes very serious;
- **regular travel functions**: this category includes all the movements of persons and goods that contribute to the workings of society and, in particular, of the economy. The function of a transport network is to allow these movements to be made under good conditions and, in particular, in safety. From the users' perspective (passengers and goods carriers), a loss of performance of the transport network results in wasted time, delays, the need to postpone or reorganize travel, or to defer activities and to transfer these activities to a site other than the preferred site, or even to cancel them. In a supply chain, this can result in breakdowns in supplies, with economic consequences that go as far as bankruptcy, and, therefore, job losses.

The functional criticality analysis presented in this section essentially covers these categories. However, transport networks also fulfill other functions, which should be remembered:

- support functions: users must be able to travel in safety. This includes information and safety during the extreme events ;
- ancillary functions: transport networks may fulfill other functions (ecological, social, etc.). By way of example, the network of navigable waterways also supplies drinking water to certain towns and cities, provides water for irrigation in agriculture and protects and develops biodiversity (planting techniques on the banks).

Other networks may also be physically connected to the transport network, such as the telecommunications network in constructions. In this kind of configuration, the transport network and the other networks are probably exposed to the same climate hazards, in which case it may be useful to study their functional criticality at the same time.

5.2 - Principles of the functional criticality analysis

The fundamental goal of the functional criticality analysis is to determine the consequences of a failure in a transport system on the functionality of the network. The functional criticality analysis identifies the systems whose unavailability has serious consequences. And if these systems are vulnerable to climate hazards, then they must receive priority treatment.

In practical terms, and irrespective of the origin and the nature of the failure, for the users, it results in a loss of performance (a road, a station or an airport becomes unavailable, causing delays, waits, etc.), or in a loss of connectivity, in other words the loss of the possibility to travel (a destination, or even a whole region, can no longer be accessed by road, by rail, etc.). Therefore, the functional criticality analysis can be conducted from one of these perspectives, or both.

5.2.1 - Losses of connectivity of a transport network

A functional criticality analysis applied to losses of connectivity is particularly helpful in verifying that the network guarantees access for the basic or emergency services. It is also relevant from an economic and social point of view, if the loss of connectivity lasts for a long time.

If people can no longer reach their place of work or study, or if the supply chains are broken for a long time, the economic and social consequences can be serious.

In practical terms, the goal consists of determining whether a failure or a series of failures bar access to a certain number of zones, or prevent people from reaching a certain number of destinations that are considered to be essential. Take the simple example in Figure 5, which shows whether a hospital can be accessed from a given place of residence. Two cases are considered, which have different numbers of available routes.

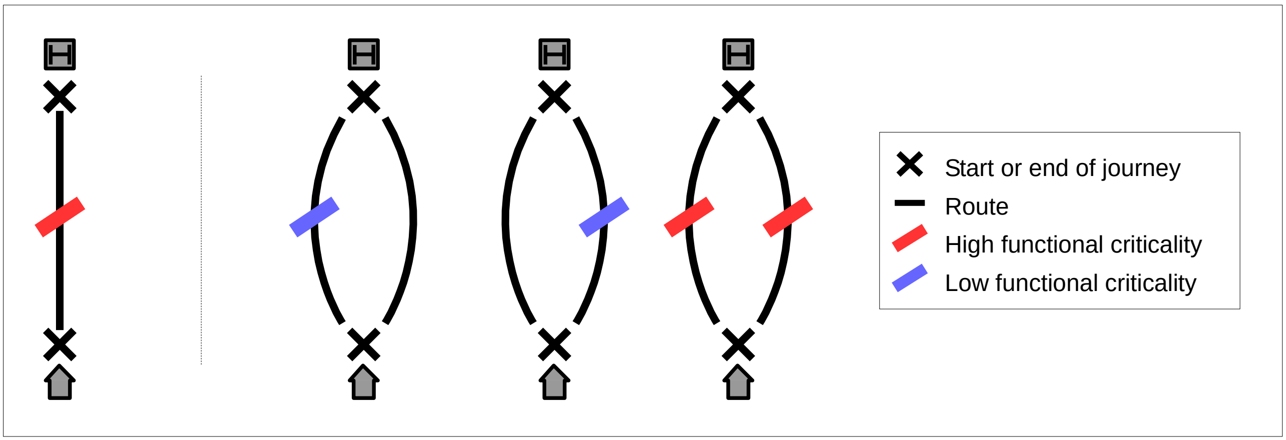

Figure 5: Functional criticality from the perspective of connectivity

If there is only one route between the two, the functional criticality of this route is very high. If this route is cut (a section of road or a junction is blocked further to a weather event), then the inhabitants of the zone in question no longer have access to health care. If there are two possible routes, then, taken individually, neither one of them has a very high functional criticality, but it is very important to prevent both routes from being cut at the same time.

5.2.2 - Deterioration of the performance of a transport network

Here, we consider the case in which the transport networks remain globally functional further to weather events. It is still possible to travel from one place to another, but the performance of the networks is degraded for a relatively long time, which allows the users to reorganize themselves. The disruption that occurs immediately after the weather event is not taken into consideration.

In concrete terms, these failures may take the form of roads, junctions, stations or airports that become unavailable, and oblige the users to take other routes or to postpone their travel, or oblige the operators to provide alternative solutions. They can also result in losses of capacity, causing delays, congestion and waiting times superior to those that the users would usually encounter, if the transport network was intact.

In this case, the functional criticality analysis consists of determining whether the users are impacted heavily. This analysis can be relatively simple if it concentrates on only one part of the transport network. Let's take the example of an airport with several accesses by road. If one of the accesses is cut, certain users will have to take another route, which can be calculated. If all the accesses are cut, then the airport becomes unusable. In this case, the impact for users is harder to measure. Is there another airport nearby? Are other modes of transport available? In order to precisely answer these questions, a broader scope needs to be considered.

The functional criticality analysis becomes more complex if the complete network is taken into consideration, because it is then helpful to determine how the users will adapt.

They can take another route, which takes longer, and may also make the users of the new route lose time too. The functional criticality of a given system in a transport network depends, in particular, on its place and its role in the network.

The simple case below illustrates this notion (Figure 6). Consider a network of two roads connecting two points, between which there is a lot of traffic. The capacity and the length of these roads may vary.

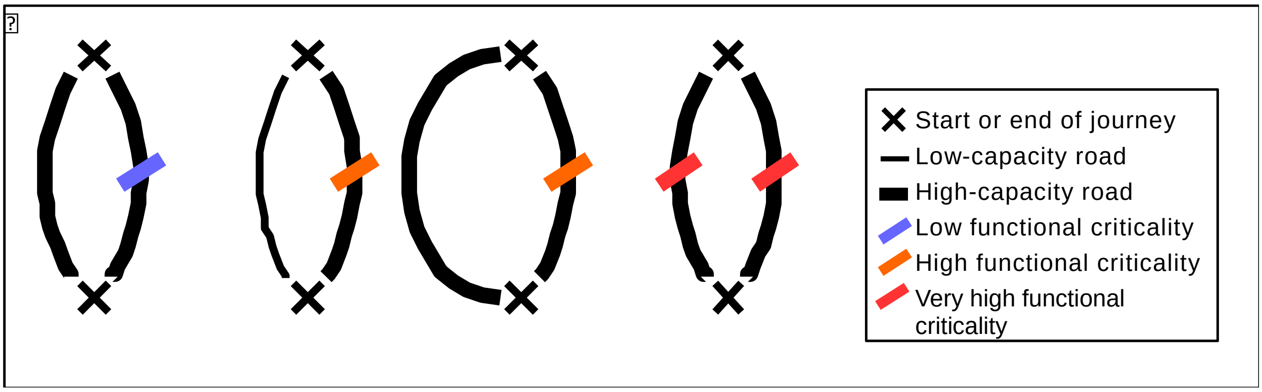

Figure 6: Functional criticality from the perspective of performance

In this case, the gravity of the consequences of one of the roads becoming unavailable varies:

(a) there are two high-capacity roads: the loss of one of the roads is not very serious for the users as they can use the other one;

(b) one of the roads has a low capacity: if the high-capacity road closes, there is a problem, because many users will take to the low-capacity road, resulting in congestion and problems for the users who already use it;

(c) the second road is much longer than the first one. If the first road is closed, then users have to make a long diversion;

(d) both roads are closed: a potentially serious connectivity problem occurs, because it is no longer possible to reach the destination.

It is difficult to generally apply this approach to complex transport systems. As we will see below, transport demand forecasting models can be used to conduct this type of analysis.

5.3 - Conducting a functional criticality analysis

The methods used to conduct functional criticality analyses are very diverse. This section presents some of the possible approaches.

5.3.1 - Assessment of inaccessibility

The functional criticality analysis can focus on breakdowns of accessibility, either for the emergency services to the impacted zones, or of users to basic services. In this respect, there are two broad categories of approaches: analyses based on accessibility indicators, and analyses that directly indicate the networks that must absolutely be protected.

The first type of analysis is particularly relevant when checking, for example, whether people are unable to access health care centers, if one or more components of the infrastructure are unavailable. An approach of this type was adopted in Australia (Taylor et al., 2006).

This approach consists of:

- defining and calculating an accessibility indicator for each zone. If we take the example of the health care centers, then we can take the distance between each zone and the nearest health care centers, according to their categories. The Australian example uses the ARIA indicator, which was developed by the health authorities to measure access to health care ;
- identifying the infrastructure components whose unavailability has the strongest effect on these indicators. These are the components with the highest functional criticality.

It is possible to create functional criticality indicators for the zones themselves. In this case, it is no longer a matter of determining whether the unavailability of an infrastructure component has a heavy impact, but of determining whether there is a high probability that the inhabitants of a given zone will no longer be able to access other zones. An indicator of this type has been used in Norway (Jelenius and Mattson, 2006). For each zone, the connection whose loss results in the greatest loss of accessibility is identified, and the proportion of trips that are made impossible is shown on a map (Figure 7).

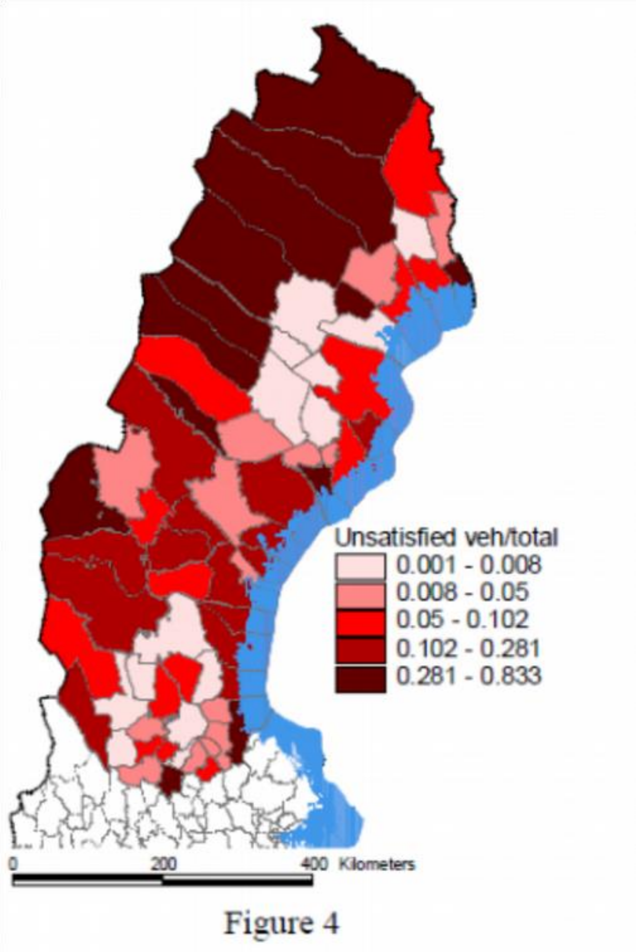

Figure 7: Loss of accessibility (share of the traffic) by zone further to the loss of the connection that causes the greatest loss of accessibility (Jelenius et al., 2006)

The second type of analysis consists of directly considering an event, such as flooding or storms, that could potentially make a large part of the infrastructure networks unavailable. This type of event would probably also impact other networks (energy, telecommunications, etc.), and multiply the human and material consequences. But it is difficult to predict the events that can have this type of impact.

The difficulty in identifying these events and their probability can be overcome by starting directly from the definition of the functions that must absolutely be maintained, and deducing the transport networks that must remain available under all circumstances in order to keep these functions accessible and operational.

This is the thinking behind the RESAU² approach (CETE Méditerranée, 2011). This approach is a continuation of the "network hardening" approaches developed in the early 2000s. It consists in asking the players involved in crisis situations:

- to identify the nerve centers, i.e., sites that must absolutely remain operational in order to limit and quickly resolve a crisis ;
- to deduce which networks, and transport networks in particular, are essential for these nerve centers to function ;
- and finally, to identify the measures that will enable these networks to remain in operation under any circumstances.

5.3.2 - Assessment of performance losses by the multi-criteria method

The functional criticality analysis can also concentrate on the regular movements of people and goods. The unavailability of a road, a junction, or any other component of a transport network will change the way in which the users use the network. In this respect, a transport system is critical, if it meets two conditions:

- it is heavily used. A road that nobody uses will never pose a problem of functional criticality ;
- there are no "good" second choices for the users. If the road is closed, users have to make a long detour or head for a place where they will saturate the network, or make the saturation worse.

According to this approach, functional criticality can be categorized using a multi-criteria method. This method has already been used in a conurbation in France (Cerema, 2014). The following factors were identified for each section: the traffic, its structure (internal, junction, transit, or a combination of the three), the alternative routes and their capacity to absorb the traffic that is carried over. The sections were categorized into four groups:

- "low importance": at least one of the alternative routes has high available capacity ;
- "moderate importance": the alternative routes only have moderate available capacity ;
- "high importance": an alternative route with low available capacity, and one or two alternative routes with moderate available capacity ;
- "very high importance": the alternative routes have very low available capacity.

This method produces the following result on a selection of six sections:

Section	Traffic	Structure	Substitute routes	Capacity of the substitute routes to absorb the estimate transfer of traffic (by type of traffic)	Conclusion: the importance of the section
Highway section 1	Very high	Internal, junction and transit	Internal: bridges 5 and 6	Low	Very important
			Junction: bridge 6 – local road 2	Low	
			Transit: none		
Local road 1 – roundabout 1 – bridge 1	Moderate	Internal, junction and transit	Internal: Local road 2 or major road 1	Moderate	Moderately important
			Junction: Local road 2 or major road 1	Moderate	
			Transit: highway section 2 – highway section 3 – Major road 1	Moderate	
Highway section 2 – bridge 2	High	Internal and junction	Internal: valley 1	Low	Very important
			Junction: valley 1 – highway section 4	Low	
Bridge 3	Moderate	Internal and junction	Internal: 5 other bridges in the conurbation	Moderate	Moderately important
			Junction: bridges 1 and 2	Moderate	
Bridge 1	Very high	Internal, junction and transit	Internal: other bridges in the conurbation	Moderate	High
			Junction: other bridges	Low	
			Transit: bridge 2	Moderate	
Bridge 4	Low	Internal	Internal: other bridges in the conurbation	High	Low

Table 9: Example of a multi-criteria analysis of some sections of a conurbation in France (Cerema, 2014)

This approach identifies the functional criticality of the various sections. This approach is relatively easy to apply on the basis of the practical knowledge of the networks of the parties responsible for the planning, operation and use of the transport networks (operators, organizing authorities, etc.). In this case, the approach concentrates on regular functionality. The question of emergency transport is not specifically addressed.

Even if this approach is designed to analyze the consequences of isolated failures, it still provides some initial information on the interactions between these consequences. For example, bridge 3 is identified as having medium functional criticality, but it would be seriously problematic if bridge 3 and bridge 1 were unavailable at the same time. Also, highway section 2 only has two alternative routes. The simultaneous closure of all three routes would have serious consequences, and certain trips would become impossible.

This type of approach has already been used in numerous situations. One interesting example is the study made by the authority responsible for transport in the state of New Jersey in the United States (NJTPA, 2013), in which the functional criticality analysis is based on a criterion slightly different from the one presented above. For each transport system, it combines the traffic and the fact that the section of infrastructure is on a route that services critical zones. The criticality of the zones is calculated on the basis of an index that combines the density of the population and the density of jobs.

5.3.3 - Assessing performance losses using a traffic model

The unavailability of part of a transport network has complex impacts on the organization of the users' movements. The advantage of the multi-criteria method that we have just described is that it is easy to implement, but its very construction limits its precision. The analysis can be refined by using traffic models.

Traffic models are generally used to forecast the impacts of a change to the transport network on traffic, typically the opening of a new road or rail line, etc. Traffic models can be used in functional criticality analyses, in which case they are not used to forecast the traffic on a new infrastructure, but to forecast the impact of the closure of existing infrastructures on users.

In concrete terms, in the functional criticality analysis of a component of the infrastructure network, it is necessary to:

- use the model in a "reference" situation, i.e., with an infrastructure network that is operating normally. In this case, the model calculates the itineraries and the users' travel times ;
- use the model when one or more transport systems are unavailable (the systems are removed from the transport network in the model). The model then calculates the itineraries and the users' travel times under these new conditions ;
- compare the two forecasts. We will then see that the itineraries have changed and, more importantly, that the travel times have increased. The model can also be used to identify losses of connectivity, or the trips that are no longer possible.

The impact of the unavailability of one or more components of the transport network essentially results in longer journey times, due to detours and increased congestion. For example, we could determine that the unavailability of a given road in a given town would increase total journey times by 1,000 hours on a typical day. It is also possible to determine which users are most severely impacted by this increase, and even to convert these indicators into a monetary value, in the same way a monetary value is put on the indicators produced by the traffic studies in the socio-economic analysis of an infrastructure project. If we assume that the value of time is €10/hour of traveling time, then the losses for the locality amount to €10,000 per day in our example. This type of result can be very useful when it is necessary to prioritize the strengthening of infrastructures, while taking the cost and the efficiency of these measures into consideration.

A study of this type was made on a conurbation in France (Cerema, 2014), in which many of the sections of the network were processed automatically. The map below shows the results.

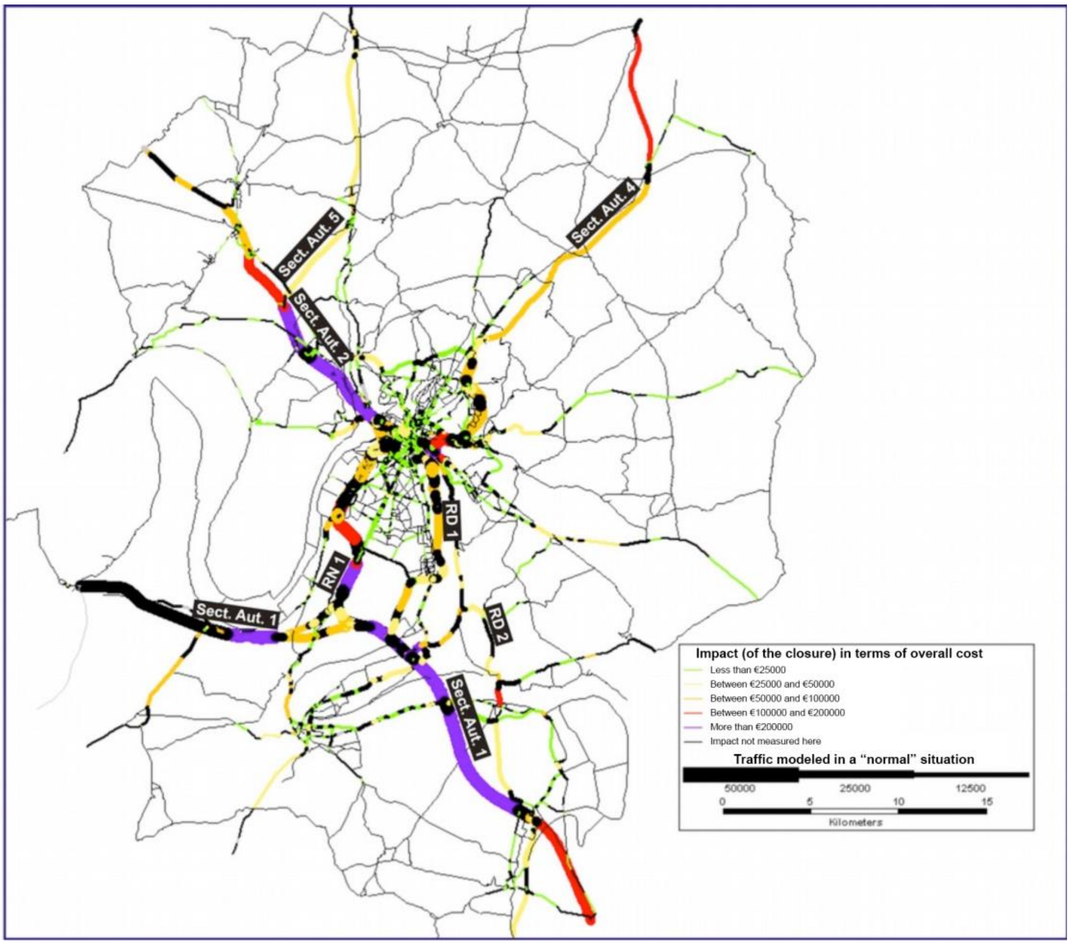

Figure 8: Systematic analysis of the functional criticality of road sections in a conurbation in France (Cerema, 2014)

The map clearly shows the functional criticality of the various roads. The heavier the traffic, the higher the functional criticality, but that is not all. In some cases, where alternative routes are available, the functional criticality is lower than in others, where there is no alternative to the road in question.

This type of systematic analysis is very interesting, but it demands particularly long machine processing times. It could make sense to conduct this type of analysis only on particular infrastructure components that are selected in a physical criticality analysis beforehand.

Studies of this type have already been conducted in Germany (Schulk, 2012), Sweden (Jelenius et al., 2006) and Switzerland (Erath et al., 2006).

5.3.4 - More details about the analysis of the consequences of multiple failures

As a general rule, the consequences of the climate hazards will be all the more serious when their spatial extension is broad, in particular in the event of multiple or chain failures, which can almost totally paralyze transport networks.

Unfortunately, we should note that the automatic process described above is not suited to the analysis of multiple failures. As a general rule, too many combinations are possible, and it is not possible to study them all within a reasonable time frame. Moreover, it would be very difficult to concisely and effectively present the results of such a gigantic analysis.

Three approaches can be defined to process multiple failures:

- the first consists of improving our knowledge of the climate hazards, in order to build scenarios that are either probabilistic or representative of the climate hazards liable to occur in concrete terms (chapter 3.2). Then, it is possible to compare these scenarios with a traffic model in order to estimate the functional consequences ;
- the second possible approach consists of studying the interactions between the components of the network. Different methods call on different types of indicators. One of these methods is used by Cerema (Cerema, 2014). This method consists of recording the traffic transfers caused by the unavailability of infrastructures for each network component. If one system receives transferred traffic more often than others, then we can conclude that it contributes to the robustness of the network. We can then define two categories of systems: those with a high functional criticality, which must not be unavailable, and those that make the network robust, and without which the consequences of the failure of the systems with high functional criticality would be even worse ;
- the third approach consists of directly defining the networks that absolutely need to be protected. In this case, we return to the RESAU² type approaches, described earlier, which are far better adapted to the problems and the timescales of crisis management than to the analysis of medium- and long-term functional consequences.

5.3.5 - Additional observations

It is important to make a few final remarks on the use of traffic models in functional criticality analyses:

- there is no such thing as a generic traffic model that can be used in all situations. Each model was built for a geographical scale (urban, regional, national model), a time scale (morning rush hour, typical day, etc.), one or more networks (road, public transport, multimodal, etc.) or one or more segments of demand (short- or long-distance mobility, passengers or freight, etc.). The goals of a functional criticality analysis of the type described here must determine the type of model used, but must also adapt to the available models. In the absence of any model, it is probably more reasonable to turn to a multi-criterion analysis ;
- current traffic modeling methods can refine the analysis of the functional criticality, by taking account of the cost of use of vehicles, tolls, service quality parameters in public transport (such as frequency), etc. The level of detail expected of the functional criticality analysis will influence the decision on whether to use a sophisticated traffic model ;
- the functional criticality analysis presented here is only relevant to the unavailability of infrastructures for at least one or two days, excluding any crises due to the climate hazard that caused the infrastructure to be unavailable. In certain cases, we have observed that this is how long it takes for the users of a transport network to become aware of the change to the network and to reorganize their travel arrangements. For shorter periods, other approaches are recommended (the feedback report on the large-scale initiative of the Lyon CETE, published in November 2013, is a benchmark on this subject) ;
- the traffic models presented here are not designed to study emergency transport. So they must only be used for functional criticality analyses that concentrate on the regular functionality of transport networks.

There is a fine balance between the scope and the precision of the analyses, the precision of the models, the calculation times, the possible simplification of the available models, etc. The report "*Plan National d’Adaptation au Changement Climatique, évaluation des enjeux trafic via l’utilisation d’un modèle de déplacement*" (Cerema, 2014) presents the alternatives and their mutual advantages and shortcomings.

Chapter VI

6 - Risk analysis

6.1 - Presentation of the risk analysis method

To summarize, the preceding steps have allowed us to:

- characterize the expected climate hazards as part of climate change that are liable to impact the network ;
- precisely describe the transport network in order to fully understand its physical vulnerability (the age of the infrastructure, the state of upkeep, etc.) ;
- precisely characterize the issues of the network, i.e., conduct a precise analysis of the network in order to fully understand its functional vulnerabilities: the layout of the network, the matrix of movements, proven vulnerabilities in the event of failures, etc.

The effective risk can be assessed by comparing all of this input. This can be done using risk matrices. These matrices classify and illustrate the risks by defining categories of physical and functional criticality. Since we have three items – climate hazards, physical vulnerability and functional vulnerability – we would have to produce a 3D matrix, which is not very practical. This problem can be overcome by creating several successive matrices:

- a physical criticality matrix that compares the climate hazards with the physical vulnerabilities ;
- and a functional criticality matrix that compares parts of the network and issues. This step was completed in the functional criticality analysis (chapter 4) and the result can be presented in the form of a matrix or a map.

These two matrices can be produced in parallel or one after the other, in any order. Once they have been created, the risk matrix can be built, which cross-references the physical and functional criticality.

The flow chart in Figure 9 shows a simplified illustration of these combinations.

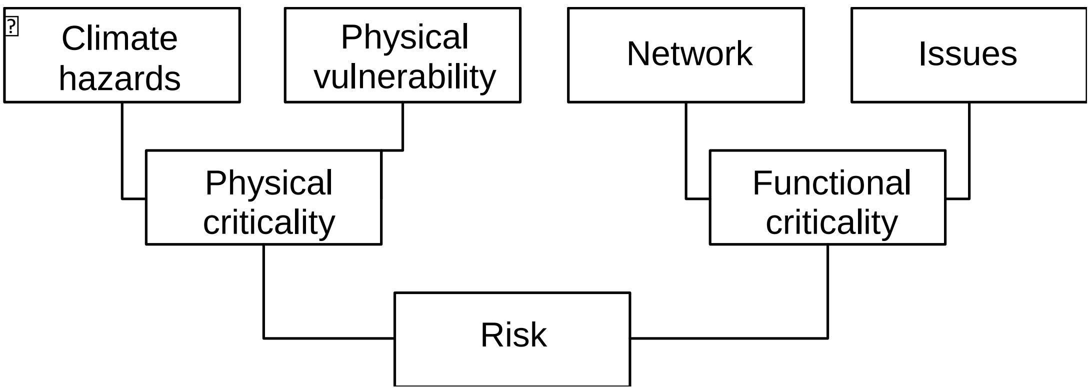

Figure 9: Risk analysis flow chart

Note that the choice of the scale of the risk analysis was made at an earlier stage, when the objectives of the risk analysis were defined (21). This common scale determines the result of the risk analysis and the operating method. If the analysis is made over a large territory, the functional criticality can be analyzed in sections of the networks. In this case, the physical criticality of the studied section will be analyzed. By way of example, it is possible to study the global vulnerability of transport systems section by section.

Then, the analysis can be refined, for example by analyzing the physical criticality of the systems in a section with a high risk level. The risk analysis can then define the systems most at risk in the given section. At this point, the components can be analyzed in detail. It is also possible to directly conduct a very detailed risk analysis of the systems, or even the components, if the territory is very restricted. This could be the case for urban networks, or if the analysis concentrates on a particular transport system (STAC 2013).

6.2 - Producing the physical criticality and risk matrices

6.2.1 - Calculating the physical criticality and risk ratings

At each level of the risk analysis, the climate and infrastructure experts rated each climate hazard and each physical vulnerability, and analyzed the functional criticality. Now, in order to perform:

- the physical criticality analysis, it is necessary to measure the potential impact of a climate hazard according to its occurrence and/or its intensity on the network. This impact also depends on the physical vulnerability of the networks. It is necessary to compare the rating of each climate hazard with each physical vulnerability rating. This produces a physical criticality rating ;
- the risk analysis, by cross-referencing the physical criticality rating with the functional criticality rating. This produces a risk rating.

In simplified terms, the following formulas are used to calculate the ratings :

- physical criticality rating: climate hazard rating x physical vulnerability rating ;
- risk rating: physical criticality rating x functional criticality rating.

Producing these two ratings requires very good knowledge of the issues on the one hand, and of the climate hazard and the physical vulnerability on the other, but also an in-depth understanding of the combination of these two factors, as we explained in the preceding chapters.

6.2.2 - Calculating the physical criticality ratings

The physical criticality matrix (Table 10) can be built using the results obtained above (Tables 5 and 8).

Physical criticality matrix				Occurrence and/or intensity of the climate hazard		
				Climate hazard no.1	Climate hazard no.2	…
				Note	Note	…
Networks studied	Individual system no.1	Component no.1	Vulnerability rating			
		Component no.2	Vulnerability rating			
		…	…			
	Individual system no.2	Component no.1	Vulnerability rating			
		Component no.2	Vulnerability rating			
		…	…			
	…	…	…			

Table 10: Example of a physical criticality matrix

The physical criticality is rated using the formula shown above: physical criticality rating = climate hazard rating x physical vulnerability rating. For example (Table 11), if we take a vulnerability of level 3 and a climate hazard of level 2, the rating is 3x2=6.

Physical criticality matrix				Occurrence and/or intensity of the climate hazard
				Climate hazard no.1
				Rating: 2
Networks studied	Individual system no.1	Component no.1	Rating: 3	Physical criticality = 3 x 2 = 6

Table 11: Example of the calculation of the physical criticality determined by the product of a climate hazard rating times a vulnerability rating

The ratings must be calculated for all the components (and/or systems) and climate hazards. This process results in the physical criticality matrix, with a physical criticality rating for each component (and/or system) and climate hazard.

6.2.3 - Calculating the risk ratings

Once the physical criticality ratings have been calculated, it is possible to assess the risk. Each physical criticality rating (of a component or a system when faced with a climate hazard) is cross-referenced with each functional criticality rating, in the same way as the climate hazard ratings were multiplied by the physical vulnerability ratings (chapter 6.2.2). The risk matrix (Table 12) can be produced using the physical criticality matrix produced earlier (Table 10). As a general rule, the functional criticality is measured on a section of the network or on systems (bridges, tunnels, roundabouts, etc.), but does not go down to the component level (bridge pile, etc.).

Risk matrix		Climate hazard no.1	Climate hazard no.2	…
Network studied	System no.1	Physical criticality x functional criticality of system no.1	Physical criticality x functional criticality of system no.1	…
	System no.2	Physical criticality x functional criticality of system no.2	Physical criticality x functional criticality of system no.2	…
	…	…	…	…

Table 12: Example of a risk matrix

6.2.4 - Definition of levels of risk

The group must now define the risk levels. First, the risk limits must be defined: low, high and very high in a three-level scale. The number of levels of risk varies, depending on the required degree of precision and the networks being studied. The more rating levels in the scales of physical and functional criticality, the more refined the characterization of the levels of risk. For example, with a five-level rating, the range of possibilities is broader and the levels can be calibrated to be more or less severe. With a three-level rating, cross-referencing these three items does not produce a significant "probability of risk", but marks out the risk zones that are "acceptable" and "unacceptable". It is at this point that the level of sensitivity of the contracting authority or the operator to a given climate hazard, vulnerability, etc. may come into play. In any case, the party conducting the risk analysis chooses the rating levels and the expected consequences. The calibration required to make these choices is a very important exercise.

In order to define these levels of risk, it is necessary to know the different risk ratings that can be used. Let's return to the example above:

- the rating scales of the climate hazards and the physical vulnerabilities have four levels, so the physical criticality ratings can range from 1 x 1 = 1 to 4 x 4 = 16, as shown in Table 13 (physical criticality rating = climate hazard rating x vulnerability rating) ;
- if the scale of functional criticality also has four levels, then the risk ratings can range from 4 x 1 = 4 to 4 x 16 = 64 (risk rating = functional criticality rating x physical criticality rating), as shown in Table 14.

Potential physical criticality ratings			Physical vulnerability rating			
			4	3	2	1
			Extremely high	Very high	Moderately high	Not very high
Climate hazard rating[9]	4	Likely	4 x 4 = 16	4 x 3 = 12	4 x 2 = 8	4 x 1 = 4
	3	Rare	3 x 4 = 12	3 x 3 = 9	3 x 2 = 6	3 x 1 = 3
	2	Unlikely	2 x 4 = 8	2 x 3 = 6	2 x 2 = 4	2 x 1 = 2
	1	Extremely unlikely	1 x 4 = 4	1 x 3 = 3	1 x 2 = 2	1 x 1 = 1

Table 13: Physical criticality ratings that can be produced with four-level scales of physical vulnerability and climate hazards

Potential risk ratings		Potential functional criticality ratings			
		4	3	2	1
Potential physical criticality ratings	16	64	48	32	16
	12	48	36	24	12
	9	36	27	18	9
	8	32	24	16	8
	6	24	18	12	6
	4	16	12	8	4
	3	12	9	6	3
	2	8	6	4	2
	1	4	3	2	1

Table 14: Risk ratings that can be produced with four-level scales of physical vulnerability, functional criticality and climate hazards

After calculating the risk ratings, a limit of acceptable risk must be set. In other words, a level for which no immediate adaptive measures are required. Depending on the rating obtained by

[9] In this example, the rating is based exclusively on the probability of occurrence.

comparing the functional and physical criticality of the networks, the risk is assessed as being below or above this limit, and it is possible to determine where action is required. The number of levels of risk can vary, depending on the required level of precision and the networks in question.

In the example above, three levels of risk were defined, each with a color code:

Risk level	Value	Required action
Intolerable	27-32-36-48-64	The risk is unacceptable. Preventive/protective measures are necessary
Severe	9-12-16-18-24	The risk can only be accepted if the preventive/protective measures are too difficult to implement
Tolerable	1-2-3-4-6-8	The risk could be accepted, but it must be periodically re-assessed

Table 15: Examples of levels of risk with color codes

This scale of levels of risk can be used to classify the risks according to the rating obtained by multiplying the physical and functional criticality ratings. The chosen scale can be applied to the calculation matrix (Table 16):

Potential risk ratings		Potential functional criticality ratings			
		4	3	2	1
Potential physical criticality ratings	16	Intolerable	Intolerable	Intolerable	Severe
	12	Intolerable	Intolerable	Severe	Severe
	9	Intolerable	Intolerable	Severe	Severe
	8	Intolerable	Severe	Severe	Tolerable
	6	Severe	Severe	Severe	Tolerable
	4	Severe	Severe	Tolerable	Tolerable
	3	Severe	Severe	Tolerable	Tolerable
	2	Tolerable	Tolerable	Tolerable	Tolerable
	1	Tolerable	Tolerable	Tolerable	Tolerable

Table 16: Example of a risk matrix with color codes

This matrix can be used to draw the map of the risks on the networks.

6.3 - Towards risk mapping: comparing transport data with climate data using the chosen risks matrix

Once the scale of risks has been chosen, the group must produce a table containing the systems (and components) of the selected networks, the selected climate hazards and an assessment of the risk, produced by comparing this data for each event. This table can be presented as follows:

Example for a subway type network	Climate hazard no.1	Climate hazard no.2	…
Station U	Risk level	…	
Station V	…		
Main section in tunnel			
…			

Table 17: Example of a transport-climate hazard matrix

For each comparison between a component or system in the networks and each climate hazard, it is necessary to enter the determined level of risk, e.g., intolerable, severe, tolerable (Table 15). When applied to all the parts of the transport networks for all the selected climate hazards, this method can be used to jointly complete a table with dual inputs that recaps the details of the networks, the climate hazards and the risk estimates. This table can constitute the final result. Thanks to the color codes (shown in red in the example in this chapter, Table 16), it shows which risks are intolerable.

Annexes

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7 - Acronyms

ALADIN: limited area, dynamic adaptation, international development

ANR SCAMPEI: French national research agency (ANR), climate scenarios for mountain areas: extreme events, snow cover and uncertainties (SCAMPEI)

AOGCM: Atmosphere-Ocean General Circulation Model

ARPEGE: small-scale and large-scale research action

CEREMA: Center for studies and expertise on risks, environment, mobility, and urban and country planning

CERFACS: European center for research and advanced training in scientific computation

CETU: center for technical research into tunnels

COUNTERACT: cluster of user networks in transport and energy relating to anti-terrorist activities

CNRM: Météo-France national meteorological research center

DGITM: directorate general for infrastructure, transport and the sea

DRIAS: French regional climate change scenarios for impact and adaptation of our society and environment

DTecEMF: technical division for water, sea and waterways (CEREMA, formerly CETMEF)

DTecITM: technical division for transportation infrastructures and materials (CEREMA, formerly SETRA)

DTecTV: technical division for territorial development and urban planning (CEREMA, formerly CERTU)

DTer: territorial divisions (CEREMA, formerly CETE)

GES: greenhouse gases

GICC: management and impacts of climate change

IPCC: Intergovernmental Panel on Climate Change

IPSL: Institut Pierre-Simon Laplace

IQOA: quality index of constructions

IQRN: quality index of the national highways network

LMDz: zoom climate and meteorology laboratory

MAR: regional atmospheric model

MEDDE: Ministry of Ecology, Sustainable Development and Energy

MEDTL: Ministry of Ecology, Sustainable Development, Transport and Housing

PNACC: national climate change adaptation plan

RFF: French rail network

SCAMPEI: climate scenarios for mountain areas: extreme events, snow cover and uncertainties

SCRAE: regional climate-air-energy plans

SETRA: technical department for transport, roads and bridges engineering and road safety

SREX: special report on managing the risks of extreme events and disasters to advance climate change adaptation

STAC: civil aviation technical center of the French civil aviation authority

STRMTG: technical department for mechanical lifts and guided transport systems

VNF: navigable waterways of France

WG: Working Group

8 - Glossary

The definitions below are specific to this guide.

Climate hazards: weather events outside the transport system characterized by an intensity, a spatial probability of occurrence and a probability of occurrence in time. In this report, only extreme climate hazards that cannot be easily anticipated and localized, are taken into consideration. They include both extreme weather events and their consequences on the territory: heat waves, forest fires, periods of heavy rain, flooding, landslides, extreme winds, marine flooding, etc.

Functional criticality analysis: the cross-referencing of the issues and the functional vulnerabilities of transport networks.

Physical criticality analysis: the cross-referencing of the climate hazards and the physical vulnerabilities of individual transport systems.

Risk analysis: the cross-referencing of climate hazards, the physical or functional vulnerability and the issues of the infrastructures, or the comparative analysis of the physical and functional criticality.

Transport component: part of a transport system. For example, in a rail network: rails, overhead lines, etc.

Importance/issues: in this guide, the importance/issues of a transport system are the maintenance of its functions as a means of mobility that services and provides access to certain zones and, finally, regarding the movements and management of the emergency services.

Transport system: part of a transport network. For example: bridge, tunnel, roundabout, etc.

Functional vulnerability of a transport system: the vulnerability of the system on a macroscopic scale, which depends on the functional characteristics of the network of infrastructures, its capacity, its meshed character, etc.

Physical vulnerability of a transport system: the vulnerability of the components of the system, which depends on the physical characteristics of the components of the infrastructure, their strength, their behavior, etc.

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10 - Case studies

10.1 - The National Climate Change Adaptation Plan – Assessment of traffic issues using a movements model

The impact of climate change on transport networks will probably become worse over the years. Transport systems play an important economic role and are sensitive to numerous climate hazards. In order to prepare the improvements that are required to make transport infrastructures resilient and resistant to climate change, it is necessary to analyze their vulnerabilities. This is the reason why PCI MOD² wrote this report.

In a network of infrastructures, certain links are more sensitive to disruptions than others. Disruptions can result in an overall increase in the length of journeys and congestion. There are also links that are not vulnerable themselves, but that contribute to the overall robustness of the network. If these links are unavailable, disruptions could have far more serious repercussions, because the alternative routes would be few and not robust.

The goal of this study is to design a methodology for the assessment of vulnerability and the importance of the roads in a transport network. It concentrates only on the highways network and looks at localized disruptions in the medium term, in other words, once drivers have adapted their journey routes, but without changing their means of transport or destination. Impacts that cause damage and injuries are not covered by this report.

10.1.1 - Assessment of the issues

The study is broken down into two parts. The first part presents the aspects that are required to understand the problem using a simple example: the closure of a specific section of the A13 highway between Paris and Rouen. This simulation uses a static traffic model applied to the Seine estuary-Paris corridor. The consequences are presented and discussed in detail, looking at numerous indicators, such as journey times, the overall cost and accessibility. This example highlights a significant variation of all the indicators, and in the total time spent on the network in particular, which increases by about 83,000 hours per day, and the distance covered on the network, which increases by 1 million kilometers.

In this first stage, the example is then extended to several sections of the A13 highway and to various main roads in the Seine estuary-Paris corridor. The same indicators are used as in the first example. These examples show that the analysis of the initial traffic alone is not a satisfactory indicator to analyze the vulnerability of a section of road. The most relevant indicator that can be used to observe the overall importance of a transport network using a traffic model, is the total cost. Nevertheless, the model was used without varying the choice of destination or the modal distribution. This simplifying hypothesis probably produced an overestimation of the impacts.

The second part of the report presents a global methodology to analyze the issues of a transport network. The process consists of individually testing all the sections of a road network and quantifying the impacts and, therefore, the overall cost. This method is applied to two existing models: the model of the Seine estuary-Paris corridor and the model of the Rouen conurbation. For both models, the roads that cause the sharpest rise in the total costs are not necessarily the roads carrying the most traffic. The tested methodology is simple, but it demands a traffic model that is sufficiently simplified to limit the necessary machine processing time. When this is too complex, the report recommends that a certain number of sections considered as critical should be selected.

If there is no traffic model, the study proposes a simplified method. This method identifies how each section contributes to the resilience of the network by identifying the nature and the volume of the traffic and the alternative routes. The capacity of the itineraries to absorb the extra transferred traffic is qualitatively rated. Then, on the basis of the results for each itinerary, the importance of the section is determined. However, anyone wanting to use this type of method must have very good knowledge of the structure of the traffic on the network.

The following diagram summarizes the method proposed for the analysis of issues related to the vulnerability of a transport network.

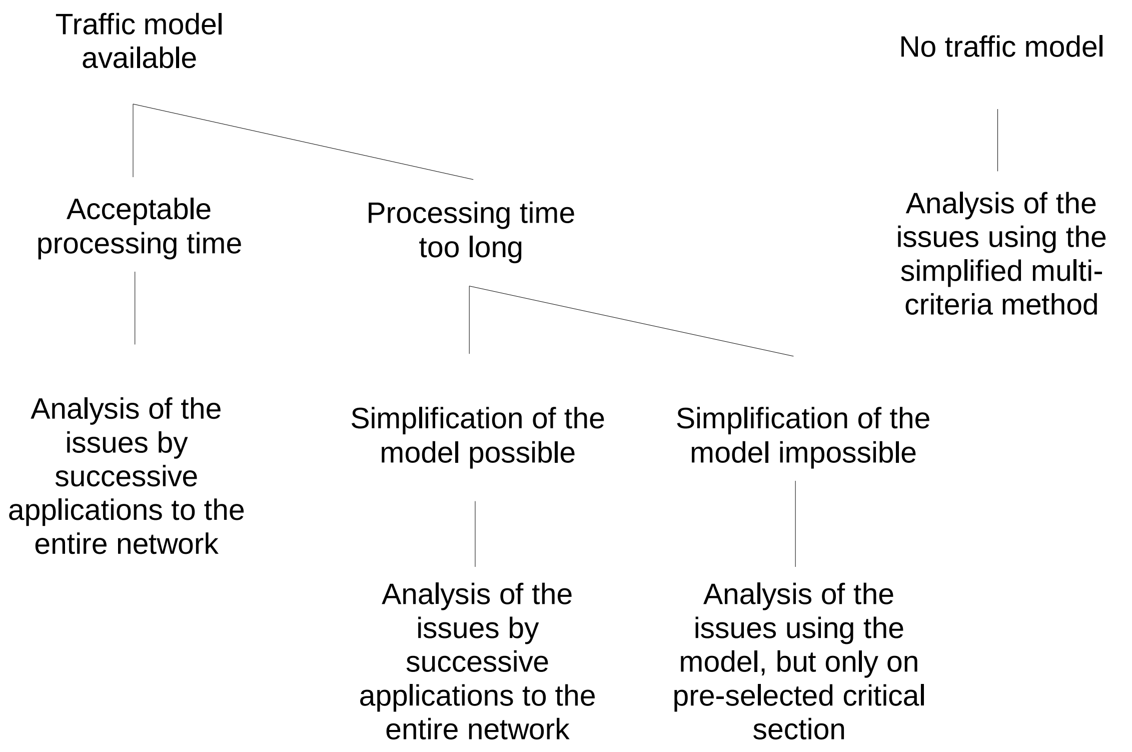

Figure 10: Methodologies for the analysis of issues related to the vulnerability of a transport network

However, it should be remembered that this method only considers the closure of isolated sections, while in the event of a climate hazard, there is a possibility that several sections will close at the same time. In this case, the automatic method is not suitable, and it is necessary to resort to a simplified analysis of a selection of sections.

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10.2 - Assessment of the cost of the impacts of climate change and adaptation in France

This study aims to evaluate the extra costs incurred by the impact of a heat wave or temporary or permanent submersion due to the rise in sea level on a publicly-managed major road in the national highways network in metropolitan France.

10.2.1 - Economic context

Land transport infrastructures play an important part in the French economy. In 2007, the added value of the transport sector represented 4.2% of the GDP. "Expenditure on the production of transport infrastructures alone, of all modes of transport, represents about 0.6% of the GDP."

This study only covers the roads network, amongst the different types of land transport – roads network, rail network and navigable waterways. The roads network does in fact represent the greatest linear distance of infrastructures: 1,027,002 km in 2007, compared with 31,154 km of rail tracks and 8,501 km of navigable waterways. It also represents a predominant share of the transportation of goods (almost 87% of the ton-kilometers covered in France) and passengers (83.8% of the passenger-kilometers covered on all of the land infrastructure networks).

The study only covers the publicly-managed major roads of the national highways network, operated directly by the State. While it only represents 1.2% of the linear distance of roads in France, it represents a significant share of traffic: 25.5% of total road traffic in France in 2007. The other types of networks could not be studied due to a shortage of data.

The cost of fully reconstructing the publicly-managed major roads of the national highways network (RRN NC) in service on December 31, 2007, (12,359 km) would have been €121,309 billion under the economic conditions in August 2008. The asset value of the RRN NC would then be €9,815 million per km. The cost of repairing the network (pavements and constructions) is estimated at €3,014 billion, or €224,000 per km.

10.2.2 - Extra costs incurred by the impacts of a heat wave on the RRN NC

Main impacts of a heat wave on the road infrastructures

The climate is one of the parameters to be taken into consideration in a road project. Changes in temperature are taken into consideration in different manners in road projects. A change in the temperature can influence the structural design of the pavements, the choice of materials and the formulation of the asphalt. Wheel tracking by creep or penetration appears to be the main impact of a rise in mean temperatures or periods of severe heat. This problem can be solved by over-classifying, without changing the type of product. It is difficult to assess the economic impact of this change, because prices are given by type of product. Finally, changing the formulation of the asphalt does not appear to incur any significant extra costs.

Method for assessing the economic cost of a heat wave

The cost of the impact of a heat wave on the RRN NC was evaluated using three complementary approaches:

- a field survey amongst the decentralized departments of any damage to pavements and constructions during the 2003 heat wave ;
- an analysis of budgetary data in order to determine whether the 2003 heat wave incurred any additional maintenance costs. At the same time, an examination of the quality indexes of the national highways network (IQRN) and constructions (IQOA) for the RRN NC revealed whether quality deteriorated, in the same year, due to incomplete repairs ;
- and finally, a benchmark assessment based on an international bibliography. An attempt was made to quantify the cost of the impacts by directly transposing cases from abroad into France. But this method of assessment involves numerous uncertainties. It is based mainly on the extrapolation of data regarding the 2003 heat wave in France alone, and data on

road works in the UK and Australia, where the climate and the design, maintenance and use of the roads are different from those in France. It does not take account of any geographical specifics. Finally, the economic evaluations only take the global value of the network's assets and any repair costs into account.

Results of the field survey of the 2003 heat wave

According to the field survey on the 2003 heat wave in 22 decentralized departments, the heat wave caused frequent occasional damage, but no general disorder. Regarding constructions, the drought caused the soil and fill to shrink, especially for clay soils. The shrinkage caused cracking in bridges and the settlement of fill. On the highways network, the heat wave resulted in additional bleeding of the coatings and micro-asphalts, plus a significant increase in transverse cracking, with the appearance of beads caused by buckling slabs, in roads made with hydraulic binders.

According to the experts who contributed to this report, in view of the absence of any wide-scale damage and the relative uncertainty about the causes of the damage observed, it would appear that the current specifications for the structural design and maintenance of pavements are satisfactory, despite the rise in temperatures. Nevertheless, little is known about the potential impacts of recurrent heat waves. They could have more serious economic impacts on pavements carrying heavy traffic and if the dessication of the soil creates damage that propagates from the foundations of constructions.

Results of the examination of budget data and the IQRN and IQOA

The analysis of the budget data did not allow the economic impact of the 2003 heat wave to be evaluated. There are a number of reasons: the data is aggregated at a national level, expenditure is presented by type of maintenance, without any indication of the reasons behind the need for maintenance, etc.

The analysis of the IQRN showed a general deterioration in the state of the networks since 1995/1997. According to the report, "this deterioration is closely linked to the resources allocated to highway maintenance since this period." The 2003 heat wave does not appear to have had a significant impact on this state, but it is possible that a network in good condition would be less impacted in the future than a partially degraded network. The examination of the IQOA produced similar results: "We observed a slow deterioration in the constructions that demands surveillance and maintenance and rehabilitation actions in order to maintain a good quality of service on the network."

As for the field survey, **no significant impacts of the 2003 heat wave on the quality of the network could be determined. The examination of the budget data did not allow us to come to any conclusions about the economic impact of the heat wave on the RRN NC**.

Results of the benchmark assessment

In France, like in other countries, there are few works that look into the assessment of the costs incurred by the impacts of climate change on transport infrastructures. The list of bibliographical references used to conduct a benchmark is all the more restricted for the purposes of this report, which concentrates exclusively on the assessment of the costs incurred by a rise in temperature on the road networks.

A few studies contain quantified figures of the impacts of a heat wave. Studies in the UK have examined budget data on the additional maintenance costs incurred by the 2003 heat wave (Defra, 2006; Hudson, 2006). According to these studies, in the year of a heat wave, the annual maintenance budget allocated to repairs rises by 15%.

According to an Australian study (Austroads, 2004), a drop in precipitation due to a rise in temperatures would improve the durability of the pavement. This situation appears to be globally applicable in France, with a few reservations depending on the season. The study forecasts annual variations in the global maintenance costs of about -2% to +4%.

In France, the annual cost of maintaining the network in 2007 was €426 M. In 2008, it was €456 M. On the basis of the British estimate, **the annual additional maintenance costs allocated to damage repairs would vary between €64 M and €70 M in years with a heat wave**. If we apply the Australian study to France, **by 2100, the variation in annual global maintenance costs would be -€9 M to +€18 M**. This figure is in line with the British figures.

10.2.3 - Additional costs due to temporary or permanent marine flooding on the highways network

An approach by relative additional costs

In this study, the hypothesis of a 1-meter rise in sea level by 2100 was applied. Any infrastructure located below the current sea level +1 m could be affected by definitive submersion. In this case, the additional costs caused by the submersion would be equal to the mean value of the network's assets.

The risk of temporary submersion is usually assessed at a centennial level. According to joint work done by the French Naval Hydrographic and Oceanographic Service (SHOM) and CEREMA's technical division for water, sea and waterways (DTecEMF), centennial submersions were estimated in 2008 at 1.5 m NGF (general levelling of France) in the Mediterranean, and at 3 to 8 m NGF on the English Channel and Atlantic coasts. Zero NGF corresponds to the mean level of the sea in Marseille. A rise in the sea level would increase the centennial level and the frequency of its recurrence intervals. This report considers that all infrastructures located above the current centennial level +1 m will be exposed to the risk of temporary submersion by 2100. The authors of this report worked according to the hypothesis that the cost of repairing the damage caused by significant temporary submersion would be equal to 1 to 2 times the average annual cost per kilometer of repairing the national highways network.

An approach by topographical survey of low zones

Low zones are those zones located beneath the extreme centennial levels. The method used here consists of comparing the data in different topographical databases to determine the networks of highway infrastructures located in zones:

- lower than the current centennial sea level, minus 1 meter ;
- lower than the current centennial sea level ;
- lower than the centennial sea level, plus 1 meter (zones that could be submerged in a centennial event, by applying the hypothesis of a 1-meter rise in sea level).

The results show that the most impacted networks, in terms of linear distance of infrastructure, would be highways and local roads. There are disparities from one department to another. To take account of the uncertainties related to the methodology, **the report proposes to apply an additional cost of €2,000 M for major roads in metropolitan France (excluding highways), in the event of an overall rise in sea level of 1 meter**.

10.2.4 - Bibliographical references

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Hudson L. Highway asset management case study. In: *UK Climate Impact Programme method case study*. 2006, 14p.

10.3 - Climate Impacts Vulnerability Assessment – Washington State Department of Transportation Pilot Study

Since 2007, the Washington State authorities have taken a number of measures to study climate change and its impacts. In 2009, these actions lead to the creation of a team in the Washington State Department of Transportation (WSDOT) tasked with assessing the vulnerability of transport infrastructures to extreme weather events and climate change. In the same year, the Federal Highways Administration developed a methodology to analyze the risks incurred by transport infrastructures due to climate change. It also called on a number of administrative partners to test this methodology. One of these partners was the WSDOT, whose experimental results are presented here.

The WSDOT called on some of its experts and local operators to take part in workshops as part of this experiment.

10.3.1 - Inventory of the transport assets

An inventory of the transport assets owned or operated by the WSDOT was drawn up on the basis of a survey of experts. The collected data was completed using a database specific to constructions. The studied transport assets included airports, ferry terminals, four rail lines, state routes and inter-state roadways (including bridges, tunnels, pedestrian walkways, etc.), roadsides and various buildings connected to the transport networks, such as radio towers and maintenance sheds. The survey collected a lot of data with differing levels of detail. Then, the data was converted to a harmonized format that could be used in the cartographic analyses.

10.3.2 - Analysis of climate projections

The WSDOT then listed and analyzed the expected climate projections for Washington. It did this on the basis of numerous works, including an assessment report of climate change in the state of Washington (Washington, 2009) and spatialized climate data from Washington University. The following main climate tendencies are projected for the state of Washington:

- three hypotheses for the rise in sea level: +2 feet, +4 feet and +6 feet (approximately 0.6 m, 1.2 m and 1.8 m respectively) were selected and modeled;
- no significant changes in average annual precipitation amounts are projected for Washington. But the precipitation system is liable to change. Two maps were drawn up to illustrate the potential consequences on the transport assets. The first one shows the changes in the types of precipitation received by the drainage basins, which are mainly made up of rain, snow or intermediate precipitation. The second map shows the percentage changes in soil moisture for the period 2030-2059 ;
- increases in average annual temperature and the frequency of extreme heat are expected. Maps were drawn up showing the current and projected average maximum monthly temperature for June, July and August. The same applies to the average minimum temperature in winter ;
- maps of fires that occurred in the past were also used.

These tendencies were represented in the form of maps that were used in the workshops.

10.3.3 - Vulnerability analysis

The vulnerability analysis was conducted in a qualitative manner, because:

- this method produces an initial quick and global assessment of the vulnerability of the transport assets to climate change ;
- this type of analysis is preferable when the data is not rapidly and uniformly available in a consistent, quantified form.

First, the infrastructure networks were broken down into segments, where each segment could be made up of several parts of the infrastructure: pavements, tunnels, etc. These segments were then assessed by experts on the basis of two variables:

- a level of criticality, from 1 to 10. This level is based on parameters such as the level of roadway classifications, the volume of traffic, the existence of available alternative itineraries, etc.;
- the potential impacts of climate change on the transport assets, according to a 10-level scale. In order to assess these potential impacts, the experts and the operators first listed the current weather events that impact their networks. They then compared them with the climate projections using the maps that they had drawn up previously.

These two variables were then compared with a vulnerability matrix (Figure 11).

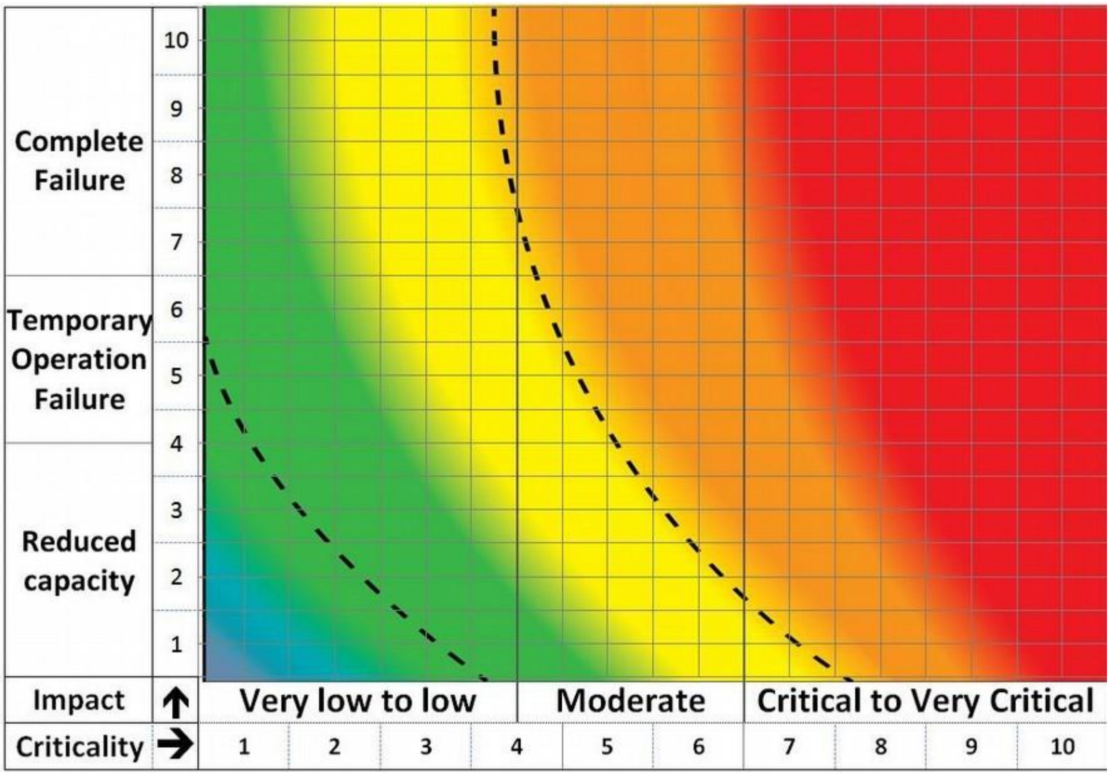

Figure 11: Vulnerability matrix. Source: WSDOT, 2011

The resulting level of vulnerability was then applied to a map (Figure 12). This level of vulnerability, the ratings attributed to each of these variables, the segment of road and other information were then entered in a spreadsheet.

10.3.4 - Conclusion

The map below shows the level of vulnerability assessed for the various infrastructures. A network segment that is shown in red is not necessarily entirely very vulnerable. Usually, only one point of the network can be extremely vulnerable. As a general rule, the most vulnerable segments are located:

- in mountainous zones ;
- above or below steep slopes ;
- in zones liable to be flooded ;
- alongside rivers that are fed by melting glaciers ;
- in zones liable to be flooded due to the rise in sea level.

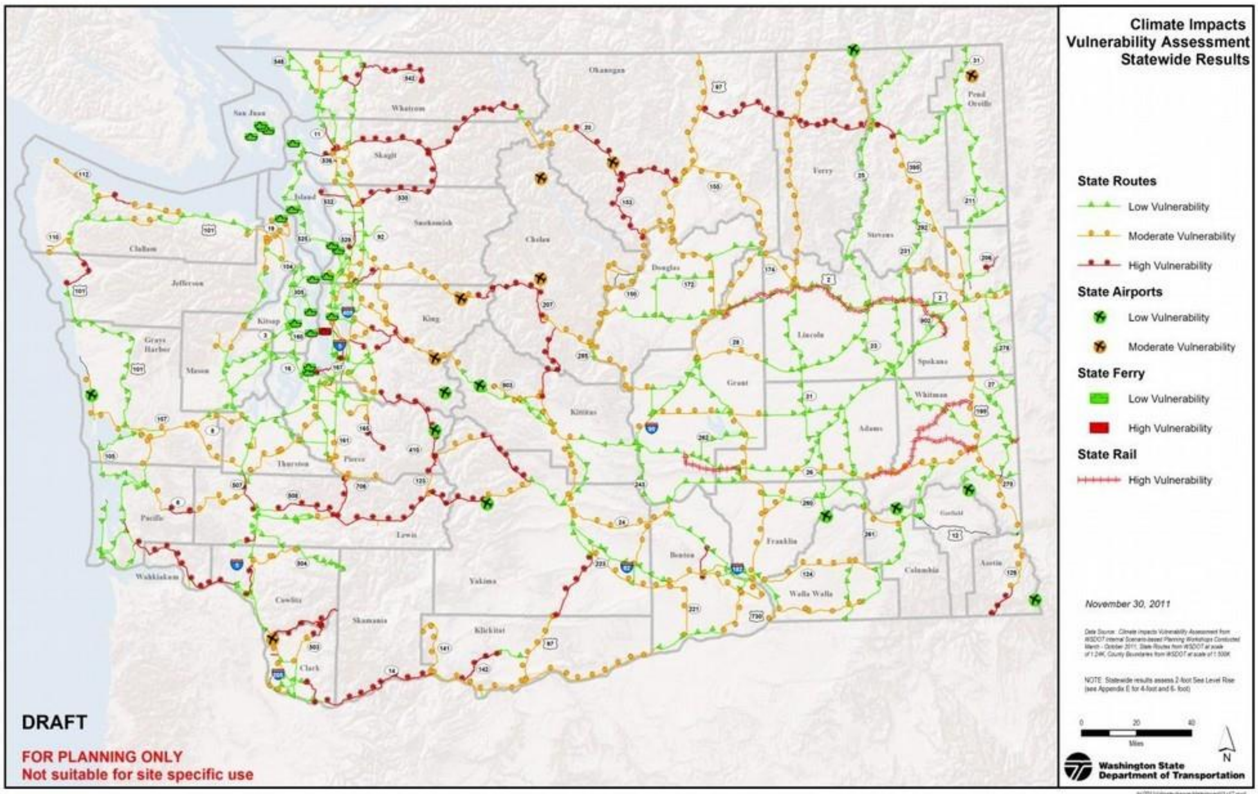

Figure 12: Levels of vulnerability of the different infrastructures. WSDOT, 2011

10.3.5 - Bibliographical references

WSDOT – Washington State Department of Transportation. *Climate Impacts Vulnerability Assessment – Report* [online]. 2011, 70p. Available from: <http://www.wsdot.wa.gov/NR/rdonlyres/B290651B-24FD-40EC-BEC3-EE5097ED0618/0/WSDOTClimateImpactsVulnerabilityAssessmentforFHWAFinal.pdf>

10.3.6 - Bibliography

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10.4 - Assessing vulnerability and risk of climate change effects on transportation infrastructure – Hampton Roads Virginia Pilot

In the United States in 2009, the Federal Highways Administration (FHWA) developed a methodology to analyze the vulnerability of transport infrastructures due to climate change. This methodology is designed to help developers and decision-makers in the realm of transport to identify their infrastructures that are the most exposed and vulnerable to climate change.

In an effort to provide developers and decision-makers with a sufficiently robust methodology, the FHWA funded pilot studies. The persons in charge of the selected studies were then able to propose improvements to the FHWA's methodology. The pilot study presented below was conducted by the Virginia Department of Transportation (VDOT) (pilot), the University of Virginia, the Hampton Roads Planning District Commission (HRPDC) and the Hampton Roads Transportation Planning Organization (HRTPO).

10.4.1 - Studied area

The studied area was the metropolitan region of Hampton Roads, in south-east Virginia. This locality is particularly exposed to flooding, in particular due to rises in sea level. It includes Chesapeake Bay, which is fed by three rivers. Moreover, most of the locality is at very low altitude.

The human and economic challenges are significant: in 2010, the locality was home to 1.7 million inhabitants. Moreover, this area is an important economic center of the state of Virginia and home to a military center that is important to the entire country. It includes one of the largest fishing ports on the East Coast and one of the biggest naval bases in the world, plus numerous other military centers and tourist industry venues.

10.4.2 - Climate change data

The generally expected climate changes include modifications to the precipitation systems, an increase in the frequency and intensity of extreme events, an increase in the numbers of days of heat waves and, finally, a rise in the sea level.

In the Hampton Roads region, the rise in the sea level is already affecting the zones at the lowest altitude. Hampton Roads is also suffering from subsidence, which is made worse by melting glaciers and erosion. The subsidence and the rise in the sea level are combining and increasing the rise in the sea level relative to the land. They could make the impacts of climate change even worse. Finally, due to the proximity of the coast, this region is particularly sensitive to tropical storms, hurricanes and tornadoes. The preceding events of this type caused huge material, human and financial damage in the region.

Numerous studies have been made of the future climate changes and their impacts on the population and the biodiversity in the Hampton Roads region. This report takes these studies into consideration. It also looked into the question of the potential impact of climate change on transport, which had previously been neglected and was hardly integrated into the long-term transport strategy in the Hampton Road region. But due to tax restrictions, it is probable that the climate data will still not be extensively used as a major decision support tool in the years to come.

10.4.3 - Adaptation of the methodological framework developed by the Federal Highways Administration (FHWA)

The methodological framework used for the Hampton Roads study comprises three major stages:

- an inventory of the transport infrastructure assets ;
- a definition of the climate change scenarios liable to impact the transport infrastructure assets. These scenarios can be combined with socio-economic scenarios ;
- a definition of new prioritization criteria that include climate change, using a multi-criteria decision-support tool.

Inventory of the transport infrastructure assets

An inventory of the transport infrastructure assets was conducted on the basis of the proposals made by the partners that took part in the study. The assets were divided into four categories. In each category, the transport assets were prioritized according to the criteria already used by developers or defined as part of this study. These categories are described below.

"Existing assets" category.

- Description of the category. These assets include the existing roads, bridges, tunnels, etc. The data on these assets comes from various sources, and in particular from the VDOT's asset management system. This system lists about 1,000 infrastructures. The decision was taken to shorten the list of infrastructures by selecting the priority infrastructures, i.e., those located on hurricane evacuation routes, those that carry heavy traffic, those at low altitude or those requiring priority maintenance. Two traffic management centers were added to this restricted list.
- Existing prioritization criteria. The long-term transport planning strategy in the Hampton Roads region proposes prioritization criteria for the transport infrastructure assets. These criteria include: involving the general public more closely in the development of the regional transport system (criterion no.1), improving the safety of transport for motorized and non-motorized users (criterion no.4), improving accessibility (criterion no.7), etc.

"Infrastructure projects" category.

- Description of the category. The long-term regional transport planning strategy includes 155 infrastructure projects on a 30-year timescale. These projects are divided into subcategories for the purposes of this study. For example: tunnels and bridges, highways, etc.
- Existing prioritization criteria. The long-term transport planning strategy prioritizes projects according to three main categories of criteria: the usefulness of the project, its economic viability and the viability of the project. Each of these categories is divided up into subcategories. By way of example, the subcategories defined for the "usefulness of the project" include the continuity and the connectivity of the planned infrastructure, its safety and security, etc.

Similarly, existing prioritization criteria were also listed for the following two categories:

- "Traffic analysis zones" category. The traffic analysis zones were chosen at random, in order to obtain an accurate representation of the geographical locations and the sizes of the zones.
- "Transport policies" category. Multimodal transport policies at different administrative levels (state, region) were chosen on the basis of their relevance and their potential impacts on the transport infrastructures and the allocation of funds dedicated to transport.

Analysis of the climate change data

The impact of climate change on the infrastructure assets covered by this report was analyzed on the basis of climate scenarios. The decision was taken not to use climate projections directly. Firstly, climate projections generally include numerous uncertainties, especially when they are made at a very local level. Moreover, the potential impacts of climate change on the infrastructure assets are also projected and also include major uncertainties, no matter whether the impacts are defined on the basis of scenarios or according to climate projections. Using scenarios also allows different climate change tendencies to be combined. As far a Hampton Roads is concerned, changes in the sea level, in the waves of storms due to hurricanes, in the number of days of heat waves and the increase in precipitation were all taken into consideration in the scenarios. For the purposes of this study, the participants defined the timescales and the intensity of the events with the heaviest impacts on their infrastructures. Finally, the scenarios can also combine climate changes with other factors that can potentially have an impact, such as socio-economic factors in particular.

In this study, the changes in the climate were combined with:

- the effects of an economic recession ;
- increased State intervention ;
- the maintenance and repair of the existing infrastructures under the current economic conditions, or in a more favorable economic context ;
- the emergence of technological innovations ;
- increased ecological deterioration.

Redefining new prioritization criteria

The assessment of the most vulnerable infrastructure assets was based on a multi-criterion decision-support tool. This type of tool is particularly well suited to assessments:

- based on criteria that are sometimes antagonistic ;
- based on empirical or incomplete knowledge ;
- without any complex modeling ;
- on a large scale ;
- that must meet several objectives.

In order to build a multi-criterion tool for the purposes of this analysis, it was first necessary to list the existing criteria used to prioritize the components in the different categories of assets (chapter 10.4.3) in a spreadsheet. Each item in the different categories was assessed according to these prioritization criteria and was given a rating. The items in the four categories and their ratings were entered in the spreadsheet.

A reference prioritization baseline was defined for all the categories of infrastructures in order to produce a comparable prioritization of the parts of the infrastructure in the four categories. The prioritizations were re-calculated according to this new basis. The new prioritization ratings are comparable, irrespective of the category under study. These new ratings were entered in the spreadsheet.

The impact of the scenarios, which take account of the changes in the climate and, possibly, of other non-climatic factors that may have an impact, on each prioritization criterion, was estimated by the experts involved in the study. Is this impact minor, moderate, or major? If the scenario is liable to have a major impact on a prioritization criterion, then the priority of the said criterion must change. In this case, new prioritization criteria are calculated for all the infrastructures. In this way, the new ratings take the impact of the scenario into consideration and, therefore, a possible climate change.

Then, it is possible to:

- know the "basic" prioritization level of each part of the assets, which does not take the potential changes in the climate into consideration ;
- know the level of prioritization of each studied asset according to a given scenario ;
- compare the impacts of the different scenarios on one or more components ;
- know which scenarios have the strongest impacts on each category of assets ;
- etc.

10.4.4 - Bibliographical references

VDOT – Virginia Department of Transportation. *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure. Hampton Roads Virginia Pilot* [online]. No date, 36p. Available from: <http://www.virginia.edu/crmes/fhwa_climate/files/finalReport.pdf>

10.5 - Study of the vulnerability of aerodromes to climate change. Methodology to assess the vulnerability of airport infrastructures to the impacts of climate change.

In the transportation systems and infrastructures section of the national climate change adaptation plan, the STAC has written a series of reports on the impacts of climate change on airport infrastructures:

- the first deliverable listed and analyzed the potential impacts of climate change on airport infrastructures and their operation ;
- the second deliverable drew up an analysis methodology and vulnerability indicators for aerodromes ;
- the third deliverable used this methodology to estimate the effective vulnerability of aerodromes open to public air traffic in metropolitan France and overseas territories.

One of the steps of the methodology consisted of a generic breakdown of the aerodrome infrastructure. This example of a breakdown is described below.

10.5.1 - Breakdown of the network

The breakdown was conducted in two iterations. In the first step, the potential impacts of climate change on airport infrastructures was assessed by breaking down an aerodrome into three large families of individual systems: infrastructure, buildings and operations:

- the airport infrastructure includes the movement aprons – taxiways and runways – plus the radioelectric, technical and signaling equipment used for takeoffs, landings and aircraft movements in these areas ;
- the buildings linked to the airport infrastructure are the control towers ;
- the operations family includes all the items linked to the operation of the airport in non-degraded mode.

Each one of these broad families can then be broken down into systems. For example, the airport infrastructure can be broken down as follows: access ways, parking lots, runway and runway systems, taxiways, terminals, offices and other buildings, gangways, control towers, operations zones, tractors, aerodrome capacity, air traffic control equipment, etc. The following table (Table 18) shows the items produced by breaking down the airport.

Airports	Infrastructures	Access	Type of access way (road, rail, maritime) Number of access ways (one or several independent means of access)
		Parking lots	A single parking lot or several parking lots, access to the parking lots. Type of parking lot (underground or open-air)

		Runway, runway systems	Number of runways Orientation Possible extension Length of the longest runway
		Taxiway	Single or several independent routes
		Traffic area	Single or several independent areas Possible extension Number of parking spaces
	Buildings	Terminals (passenger, freight)	Terminal (single? several independent terminals?) Connecting infrastructure between the terminals (automatic train service? on foot? several means of connecting the terminals?)
		Offices and other buildings	Location of the crisis control center Energy supply equipment
		Gangways	Resistance Number Sufficient alternative means?
		Control tower	Control tower electric power supply Access to the tower Thermal comfort of the tower
	Operations	Operations zones	Fuel depot
			Deicing zone or operation
			ARFF zone[10]
		Towing and assistance machinery	Storage zone for machinery, passenger buses, etc. Number of machines used to operate the aerodrome
		Capacity of the aerodrome	Planned traffic flow per day Can the traffic be transferred to another mode of transport?

[10]Aircraft rescue and firefighting (ARFF)

Table 18: Breakdown of airport infrastructure into individual systems and components Source: STAC, 2013

10.5.2 - Bibliographical references

STAC. *Étude de vulnérabilité des aérodromes vis-à-vis du changement climatique. Phase 2 : méthodologie d'évaluation de la vulnérabilité des infrastructures aéroportuaires aux impacts du changement climatique*. 2013, 72p. Study report.

10.5.3 - Bibliography

STAC. *Étude de vulnérabilité des aérodromes vis-à-vis du changement climatique. Phase 1 : les impacts potentiels du changement climatique sur les infrastructures aéroportuaires*. 2012, 80p. Study report.

10.6 - Methodology to estimate the economic impacts of disruption to the goods transport networks

10.6.1 - Consequences of disruption to the goods transport network

Global supply chains form a multi-level system made up of a multitude of entities and players distributed over a very broad geographical zone, and subjected to natural and anthropic disruptions. When such disruption occurs, the economic losses can be high, not only for the carriers and the loaders, but also for the public authorities, local syndicates and traders, suppliers of storage and distribution services, or even high numbers of consumers and economic organizations all over the country. In fact, the economic impacts can affect the whole of society.

But disruptions do not all impact the economy in the same way. The impacts vary according to the characteristics of the disruption and the disrupted chains:

- long or geographically extensive disruptions are liable to have the greatest impacts ;
- the disruption of a just-in-time supply chain or chain of high-value products will have greater economic impacts ;
- the disruption of an entire zone and all its networks could have a multitude of interconnected economic impacts that are embedded in one another ;
- on the other hand, the disruption of a single mode could result in a modal transfer, without any significant impacts on the macroscopic flows.

Moreover, the impacts also depend on the disrupted system and its response. The resilience of the system, or its capacity to adapt in order to limit the consequences of the disruption, is a major parameter in determining this response. Resilience can take the form of the network's capacity to restart the facilities and services that are necessary to transport goods, or the existence of a degree of redundancy and/or flexibility in a company that allows it to respond to the disruption with limited damage.

When disruption brings a specific mode of transport to a halt, the resilience of the system will correspond to its capacity to redirect the traffic to other modes at no additional cost. In this case, this resilience will take into consideration the availability of the capacity of the infrastructure and the service, as well as the institutional framework that allows the demand to be transported in an unexpected manner, or not. In any case, the intrinsic capacity of the other modes is not enough to determine whether it is economically possible to transfer the products to these modes. The value and the nature of the goods themselves come into play. In constricted supply chains, where the mode of transport is chosen in response to the specific needs of the goods, transferring to another and less suitable mode will generate additional costs. Therefore it is important to know and distinguish, not only the type of disruption, but also the disrupted systems, and the impacted goods.

10.6.2 - Estimating the economic impacts

The most immediate economic impacts caused by the disruption of a supply chain are the changes in the cost of transport and storage, which occur even in the event of minor disruption. More serious disruption could affect production activity, with possible negative impacts on productivity and economic production, thereby affecting macro-economic results, such as GDP. Three criteria can be used to quickly characterize disruption and determine its scale:

- its duration. How long does the disruption last ?
- its geography. Does it cover a broad geographical area, and more than one route ?
- the number of impacted links in the supply chain.

The economic impacts can be estimated by combining these characteristics of the disruption with the characteristics of the impacted goods or supply chains. But the evaluation is not intrinsic and must take other criteria into consideration:

- the nature of the methods and models used. The economic models used to assess the impacts of disruption range from a simple logical framework to complex dynamic economic simulations. The hypotheses can change the order of magnitude of the results, so it is important to know them and to take them into account;
- the questions asked. Which point of view is adopted ? For which player, or on which scale, are the impacts determined ? Disruption can very well have zero impact at a national level (the flows continue), but a negative or positive impact at a local level (the route or the mode has changed). Similarly, transferring to another mode can make no difference to the loaders, but can have positive consequences on employment in the selected mode, and negative consequences on the level of service of the infrastructure, and therefore the service delivered to the users.

10.6.3 - Methodologies used to assess the economic impacts of a disruption

Two methods are proposed to estimate the impacts of a disruption to goods transport networks. The first is a high-level method that produces a useful draft of an analysis tool. It is based on the concept described earlier stating that the economic impact of a disruption depends mainly on the characteristics of the goods, the scale and the nature of the disruption and the costs of the different components of the cost structure (transport/logistics costs, storage costs, losses of output, etc.). This method produces an estimate of the probable economic costs of any type of disruption. Figure 13 illustrates the "toolbox" concept of this method.

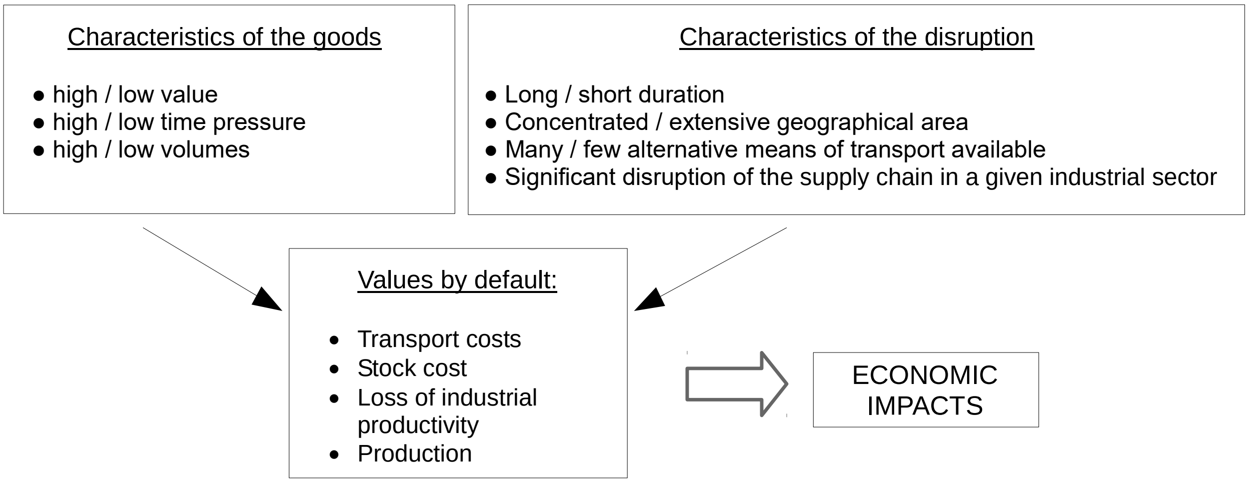

Figure 13: Basic concept of the "high-level" methodology

The second method is based on a more elaborate level of detail and analysis of the dynamics of the supply chain. This five-step sequential process (Figure 14) is used as a global and practical framework to assess a broad range of freight network disruptions and their possible economic impacts. But the use of this methodology is not totally finalized. More research needs to be conducted on the different aspects of the analytical approach, and in particular the response of the supply chain to external forces.

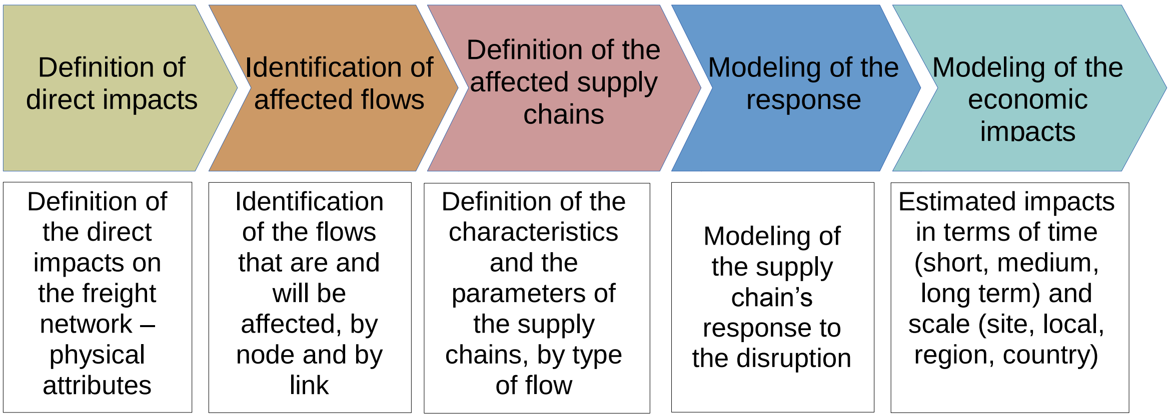

Figure 14: Diagram of the 5-step analysis/decision-support tool

Both of these methods highlight the importance of data acquisition. Efforts must be made to estimate a set of meaningful parameters that are well suited to a particular type of disruption. As far as is possible, local data should be used when estimating the cost of a disruption.

10.6.4 -Bibliographical references

Transport Research Board. *Methodologies to Estimate the Economic Impacts of Disruptions to the Goods Movement System*. Supervised by: Jenks C. W. et al. Washington DC (USA): 2012, 96p. ISSN: 0077-5614. ISBN: 978-0-309-25856-2.

10.7 - Bibliographical list of the case studies

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National climate change adaptation plan: transportation infrastructures and systems | Action 3

Analysis of the risks incurred by extreme climate events on infrastructures, systems and transport services | Collection of concepts

Based on bibliographical references, this collection of methodological concepts proposes a risk analysis methodology for transport infrastructures faced with the hazards of climate change. This involves:

- defining and analyzing climate hazards that could impact infrastructures. The hazards identified as having a potential impact are then rated based on their characteristics ;
- breaking down the transport networks studied into smaller units: systems (tunnel, bridge, etc.) and components (cable, etc.). The study of the physical vulnerability factors of the networks, systems and components can then be used to assign a vulnerability rating to them ;
- defining and rating the functional criticality of the network, which is obtained by cross-referencing the issues of the network with its characteristics.

The cross-referencing of climate hazard, physical vulnerability and functional criticality ratings defines a level of risk for each system or component. This type of analysis follows an iterative process: the number of iterations depends on the level of detail expected of the results and, therefore, the objectives of the analysis.

Upon completion of the analysis, various strategies and risk processing measures can be implemented.

Understanding and prevention of risks - Infrastructure development - Energy and climate - Management of existing infrastructures
Impacts on health - Mobility and transportation - Sustainable regions and natural resources - Sustainable cities and buildings

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