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Adaptation of transport infrastructures and networks to climate change

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Abstract

Climate, with no remaining scientific uncertainties is changing. First impacts of climate change are already felt in several fields, such as transport energy, agriculture and are expected to increase in the near future. Notably, transport networks are essential for economy and society: their adaptation is necessary. Therefore, the French National Climate Change Adaptation Plan has defined actions in its field "transport infrastructures and systems". Transversal working groups with experts of various transport infrastructures were established in 2011 and have developed a strong cooperation to address this issue. They published: *i)* a thorough review of technical, regulatory and normative standards that require an update to adapt construction, maintenance and operation of infrastructures and networks to climate trends and *ii)* a risk assessment framework to prevent future extreme weather events on transport. Aim of this paper is to present methodologies and results of both publications.

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Keywords: Transport infrastructure; transport network; adaptation; climate change; risk assessment.

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1. Aim of this article

Aim of this article is to present a major collaborative initiative of the French administration. Experts and managers worked together to address the rising issue of climate change impacts on transport infrastructures. The methodologies developed and the results obtained are discussed.

2. Introduction

Transport infrastructures are highly valuable assets designed for a long period of use. Moreover, they play a major socio-economic role. Climate change put them at risk (see e.g.: ONERC, 2008; 2009). Therefore, their adaptation to future climate trends is necessary. It is an international increasing issue, which is in France addressed by the National Climate Change Adaptation Plan (MEDDE, 2011) - PNACC[1]. The Plan is aimed at anticipating climate changes in mainland France and its overseas territories. Published first in 2011 for a five years period, renewable, it covers 20 fields such as transport infrastructures, health, energy and industry, agriculture, etc. The field "transport infrastructures and systems" deals with goods and passengers transport and anticipation of climate change impacts on transport infrastructures and mobility. It plans to develop tools and strategies to enhance infrastructures adaptation capacity. The following actions have been defined:

- Action 1: review and adapt technical standards for construction, maintenance and operation of transport networks (infrastructures and equipment) in continental France and French overseas territories;
- Action 2: study the impact of climate change on transport demand and the consequences for reshaping transport offer;
- Action 3: define a harmonized methodology to diagnose the vulnerability of land, sea and airport infrastructures;
- Action 4: map out the vulnerabilities of land, sea and air transport networks in continental France and in French overseas territories, and prepare appropriate and phased response strategies to local and global climate change issues.

Transversal working groups, at the request of the Directorate General for Infrastructure, Transport and Sea[2] of the French Ministry of Ecology, Sustainable Development and Energy and under its supervision, were established in 2011. Under direction of the Cerema[3], experts of all transport systems from different technical services of the French government: territorial and technical entities of the Cerema, CETU[4], STAC[5], STRMTG[6], from various public transport managers: VNF[7], RFF[8], SNCF[9], and from a non-profit organization: IFRECOR[10], have developed a close collaboration to address these four issues.

Amongst others, they delivered in 2015 a technical report (Cerema, 2015a) covering potential impacts of climate change on transportation infrastructures and systems, on their design, maintenance and operation standards, and the need for detailed climate projections for their adaptation (Action 1). They also published a methodology[11] entitled

[1] Plan National d'Adaptation au Changement Climatique.
[2] DGITM: Direction Générale des Infrastructures, des Transports et de la Mer.
[3] Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement (Center for studies and expertise on risks, environment, mobility and urban and country planing).
[4] Centre d'étude des tunnels (Tunnel engineering center).
[5] Service technique de l'aviation civile (Civil aviation technical center).
[6] Service technique des remontées mécaniques et des transports guides (Ropeway and guided transport technical center).
[7] Voies navigables de France (Navigable waterways of France).
[8] Réseau Ferré de France (French rail network).
[9] Société nationale des chemins de fer français (French national railway company).
[10] Initiative française pour les récifs coralliens (French coral reef initiative).
[11] This methodology is still under development, therefore qualified as interim report, however already useable.

"Analysis of the risk incurred by extreme climate events on infrastructures, systems and transport services" (Cerema, 2015b). The methodology is based on feedback from various pilot-studies (Actions 3 and 4).

All types of goods and passengers transport systems have been taken into account for these actions: aeronautic infrastructures, bridges, earthworks, guided transport infrastructures, maritime and port infrastructures, railways, roads, rope-ways, tunnels, waterways. In this article, we present actions 1, 3 and partially 4. Action 2 is still on-going and thus, will not be addressed here.

2.1. Action 1: review and adapt technical standards for construction, maintenance and operation of transport networks (infrastructures and equipment) in continental France and French overseas territories

2.2. Methodology

Adaptation to climate change is approached under the perspective of identifying the standards that may be impacted by future standard and foreseeable extreme climate trends. The dedicated working group first summarized major climate change scenarios for continental France and its overseas territories. Then, major actual climate impacts and future expected impacts on design, maintenance and operation of transport infrastructures have been identified and discussed. This served as the basis to determine which technical, normative and regulatory standards have to be updated and which are the relevant climate projections therefore.

2.3. Understanding climate change trends

On proposal of the Directorate General for Energy and Climate[12] of the French Ministry of Ecology, Sustainable Development and Energy, the climate trends used for actions of "transport infrastructures" of the PNACC are those described in reports directed by the climatologist and glaciologist Jean Jouzel (Peings Y. et al., 2011; 2012; Planton S. et al., 2012). These trends are based on the socio-economic scenarios B1 ("optimistic"), A1B ("middle") and A2 ("pessimistic") of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007). The simulations for the French continental territory and some of its overseas territories have been computed at a local geographic scale and at different time scale until 2100. Significant climate trends taken into account for action 1 are following future standard climate conditions and future expected extreme events:

- Temperature: global average temperature increase, extreme hot temperatures increase in intensity and duration, number of frost day decrease;
- Precipitations: precipitations decrease during spring and summer, snowfall decrease, increase in drought periods, extreme precipitation increase in frequency and decrease in intensity;
- ground and surface water: surface water flow increase during winter and decrease during summer, annual groundwater level decrease;
- Wind: wind conditions models are still uncertain, but extreme winds are excepted to be more frequent or intense;
- Sea level and swell conditions: pessimistic sea level increase of one meter (pessimistic projection); however, sea level at local scale is uncertain; swell conditions models are uncertain;
- Biodiversity (Lehikoinen E., et al., 2004): changes in birds' corridors are expected. This non-climate variable has been assessed, because transport infrastructures may be impacted by its evolution.

[12] DGEC: Direction Générale de l'Energie et du Climat.

2.4. Analyzing actual and future climate impacts on infrastructures

Actual climate impacts and future expected impacts have been discussed by an extended working group and summarized per climate variables and per types of infrastructure, leading to the following learning:

- Climate trends are very likely to physically impact the infrastructures, or their maintenance or operation;
- Transport networks may be impacted by changes of the above mentioned climate variables, and also by weather events such as: flooding, freeze/thaw cycle changes, storms, fog, landslides, etc.;
- To update the standards, climate variables or weather indicators that they use have to be updated or new indicators have to be defined.

Thus, the standards that may be impacted by climate changes have been reviewed. In parallel, projections and indicators requested to update the documents have been listed.

2.5. Updating documents

Hundreds of technical, normative and regulatory documents have been listed and analyzed by experts of each organization. Thus, the experts defined if the documents have to be updated or not. Methodologies differ according to transport types:

- For bridges, earthworks, roads (including urban roads) and tunnels, a keyword search in a database[13] (DTRF, 2014) has been done, keywords are climate variables described in the Jouzel's reports and climate-related variables: wind, wind speed, temperature, rain, flooding, freeze, climate, snow, radiation, heat, etc.;
- For aeronautic infrastructures, a keyword search into an international corpus of documents selected by experts has been done, with the same keywords;
- For all other transport types, experts of the working group with the help of other experts from the same organizations have analyzed the documents they had selected.

Only standards usually used or produced by the organizations represented in the working group have been taken into account. Documents including climate variables or weather indicators have been sorted into three categories:

- Category 1: documents with climate variables or weather indicators, for which climate change will have no impact;
- Category 2: normative or regulatory documents impacted by a change of the variable, that have to be updated;
- Category 3: technical document (guideline for example), for which a variable must be specified. Then, experts have to define if the document has to be updated and how.

For each type of transport, a matrix with all listed and analyzed documents, their category, the variable(s) used and the types of document (regulatory, normative, technical; for construction, maintenance or operation) has been done. In parallel to the documents analysis, experts have listed projections necessary to update the documents. Spatial, temporal or spatio-temporal projections and new indicators have been requested

[13] Documentation des techniques routières françaises (French roads technical documentation).

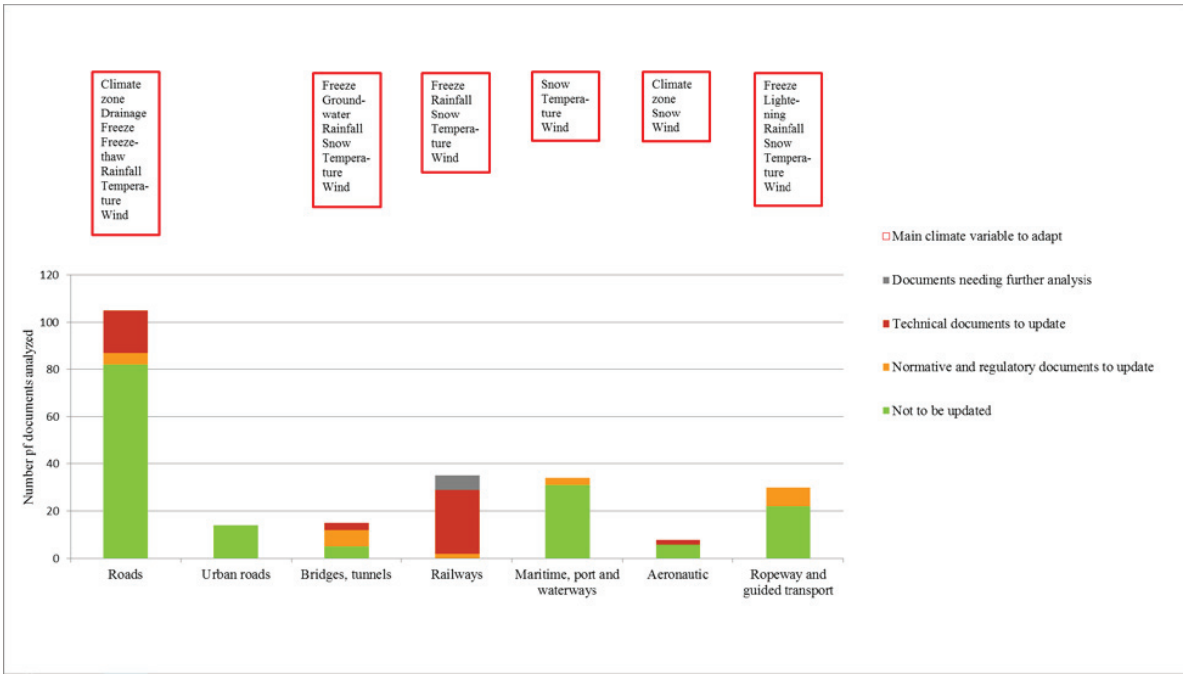

Fig. 1. Standards sorted by necessity of updating and main climate variables and weather indicators necessary for the updating.

3. Action 3: define a harmonized methodology to diagnose the vulnerability of infrastructures and land, sea and airport transport systems

3.1. Construction of the methodology

Action 1 is aimed at adapting infrastructures and transport networks to climate trends (both standard conditions and expected extreme events trends). To complete this action, a methodology has been developed as part of the third PNACC's action to anticipate future extreme weather events[14]. A first risk assessment framework has been defined by the working group on the basis of experts' knowledge and on a literature search (e.g.: Federal Highway Administration, 2012). This framework has been totally or partially tested on different transport networks types and territories. Following pilot studies have been done or are still on-going: vulnerability assessment of Le Havre port infrastructures, vulnerability assessment of Marseille metropolitan infrastructures, risk assessment of aeronautic infrastructures for France and for two international airports: Nice and Marseille (STAC, 2013), risk assessment of a waterway: Axis Seine: canal pound Suresnes – Chatou/Bougival (Cerema, 2015c), risk assessment of an urban multi-modal transport network near Nancy, automatized risk assessment of aeronautic infrastructures, automatized risk assessment of roads and railway transport for flooding events. The risk assessment framework is improved thanks to these pilot studies.

[14] Adapting design, maintenance and operation to future climate conditions is possible, but it is more difficult to take into account extreme climate value. This is why a methodology for risk assessment has been developed.

3.2. Methodology's definitions and framework

As risk addresses a wide range of fields of study, for example: natural risks, industrial risk, public security, etc. For this risk assessment methodology, the working group has proposed specific definitions.

Transport networks are composed with systems and components. Thus, it is possible to divide a transport network into ports, airports, road and railway sections; themselves composed of tunnels, bridges, platforms, etc.

Climate events are defined here as events exogenous from transport infrastructures, characterized by intensity, spatial and temporal occurrences. These events are extreme values of the climate variables described in reports on climate change (Peings Y., et al., 2011; 2012; Planton S., et al., 2012), for example: drought periods, extreme hot temperatures, extreme precipitations, number of snowfall days; and physical consequences of climate variables (with extreme value or standard value): flooding, landslides, forest fires, etc.

Extreme events impact infrastructures, whose systems and components have different physical vulnerability levels that depend from the infrastructure age, its materials, its maintenance, etc. To assess the physical criticality of a network, it is necessary to determinate which climate event will impact which system, how and at which extent.

Transport network support different functionalities: rescue services access, access to food and health centers, job access, etc. These networks have different levels of functional vulnerability according to their functionality, their capacity, alternative network, etc. Combining functional vulnerabilities with climate extreme events is necessary to assess the functional criticality.

Risk is assessed by combining the physical criticality with the functional vulnerability (Figure 2). This risk score will be useful to plan adaptation strategies. Different categories of technical or organizational adaptation measures can be defined: climate event oriented measures, for example: dikes building; infrastructures oriented measures, for example: infrastructure reinforcement; or functional oriented measures, for example: relocation of activities.

Analyzing and noting extreme events, transport infrastructures and their physical vulnerability, transport network functional vulnerability and assessing risk level by combining results previously obtained is an iterative process. It is recommended to begin with a large overview of all methodological items and then, to lead a more detailed assessment for a specific network, section of network, infrastructure or climate event. Therefore, it is possible to start with a qualitative assessment based on experts and managers knowledge and then, to lead a quantitative assessment by modeling climate, infrastructures physical vulnerabilities (e.g.: structural calculation) and functional vulnerabilities (travel models).

3.3. Preliminary stage of a risk assessment

First of all, it is recommended to define objectives and scope of the risk assessment, for example: identifying the risk level to one type of extreme event, in a specific area (e.g. an administrative area), for oldest infrastructures of an itinerary. Therefore, it is necessary to create a working group composed with infrastructures experts and managers, climate experts, land planning experts and regional planners, administration services, elected officials, etc.

3.4. Extreme events assessment

A risk assessment requires climate change knowledge. A first recommended stage is to collect information on climate change thanks to a literature search and databases studies. According to national reports on climate change (Peings Y., et al., 2011; 2012; Planton et al., 2012), and IPCC's reports (e.g.: IPCC, 2007), following extreme climate changes are expected: drought periods increase, extreme hot temperature increase in intensity and temporal occurrence, number of days of heat wave increase, extreme precipitation increase in intensity, number of days with snowfall decrease, extreme wind changes. Moreover, extreme events: forest fires, flooding, ground movements, temporary sea flooding, biodiversity (avifauna corridors evolutions, algal blooms in waterways), etc., are likely to evolve. This list of climate changes and extreme events may be modified: it is not complete; moreover, evolutions may vary depending on the territory and the time horizon for example.

For time and costs reasons, it is not possible to study all these extreme events. Thus, this list may be narrowed and adapted to the area and the objectives of the risk assessment (for example: aim of the assessment is to study vulnerabilities by one type of climate event), and the data available. Moreover, only events likely to cause impacts on network functionalities and infrastructures should be listed. Therefore, preliminary network decomposition into systems and components is expected, as well as a frame of functional vulnerability assessment.

Once the list has been created, climate events have to be characterized by intensity, spatial occurrence and temporal occurrence (length and/or frequency), at different time horizons and for different scenarios: optimistic, pessimistic. The characteristics of climate variables are available in databases (MeteoFrance, 2012) and national reports on climate change. For physical consequences due to specific values of climate variable, a literature search (DGPR, without date; MEDDE, without date) and experts' knowledge will provide information.

Finally, the parties involved in the assessment have to define a scoring scale and then, assign to each climate event a score[15]. It is not possible to characterize a climate event by the evolution of both its intensity and occurrence, thus, two scoring scales have to be defined. For example, if the intensity of extreme precipitations is expected to impact networks and infrastructures, the scale will score this intensity for a specific occurrence (annual average for example). It is also possible to score the occurrence of extreme precipitations: therefore, intensity has to fixed (precipitations over 20mm/day for example) while occurrence is projected (number of days with precipitation over 20mm/day). The final result can be gathered in a matrix with each extreme event and score.

3.5. Physical vulnerability assessment

Physical vulnerability designated in this methodology framework the inherent sensitivity of transport infrastructures. To assess the physical vulnerability of infrastructures, it is first required to divide the network into network sections, network infrastructures and components of the infrastructures and to describe each asset. A list of vulnerabilities factors has to be established by infrastructures managers with other parties. This list includes for example: age of the infrastructure, materials, expected lifetime, design rules or localization and is based on databases, experts' knowledge (CGEDD, 2013; EEA, 2012) or managers' feedback.

Then, parties will have to define together a scoring scale of physical vulnerabilities and to assign to each component, system and infrastructure a score of physical vulnerability. Therefore, it is recommended to ask the experts and infrastructures managers to consider the previous extreme events that the infrastructures have faced, the consequences of these impacts, plans developed to avoid climate impacts, etc. Potential interactions between components should also be analyzed: the failure of one component facing one climate event may impact another component, even if this one isn't vulnerable to the climate event. Such information should be collected through questionnaires, field investigations lead with experts and managers. If a more detailed risk assessment is expected, for a single asset for example, modeling studies are necessary. Workshops are then useful to define a common scoring scale; the scoring is done by each expert, in line with the scale. The final result can be presented in a matrix with each component and/or system and score.

3.6. Functional vulnerability assessment

Transport network support different types of functionalities: crucial transport functionalities, such as rescue services, firemen or police access, evacuation of persons; accessibility functionalities, such as food and health centers; and common functionalities: goods and passengers common transport services.

Climate events are likely to impact these functionalities by degrading transport connectivity, service quality, capacity, time and cost, etc. Various vulnerability assessment methodologies exist for each type of potential degradation: thus, it is necessary to choose which type of degradation will be studied.

A first group of methodologies is aimed at determining if a degradation cuts off population access to one or more crucial areas or, if it cuts off rescue services access from one area to one or more crucial areas. They are based:

- On access indicators, for example: the distance between an area and its nearest health center (see for example: Jelenius et al., 2006)

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[15] Only single extreme events are considered for the scoring stage, but the list of extreme events has to consider both climate variables changes and their physical consequences.

- On analysis of networks that must be protected. Therefore, it is necessary to identify sensitive sites, the networks that are crucial for these sites and the measures that have to be planned to protect these networks (see for example: CETE Méditerranée, 2011).

Another group of methodologies focuses on how passengers and goods transport will be impacted, concerning time issues. These methodologies are:

- Traffic modeling;
- Qualitative studies, based on multi-criteria analysis. Criteria are for example: traffic level, alternative roads, capacity of the alternative roads, etc. (see for example: Cerema, 2014; NJTPA, 2013).

Results of such studies lead to identify critical road sections (well-travelled roads or roads without substitution itineraries). The choice of a methodology depends on the type of functionalities, the length of the climate impact on the network, the type of consequences (the network is down or can still be used, but is degraded) and on the time and cost available for the study. The results are presented on a map providing a vulnerability level by section, or in a matrix.

3.7. Risk assessment

Risk level is determined through combining the scores of extreme events, physical and functional vulnerabilities. Therefore, it is necessary to score the physical criticality, by multiplying each extreme events score by each physical vulnerability score. Then, a risk level is obtained by multiplying each physical criticality score with each functional vulnerability score. It is also possible to begin with the functional criticality scores. The final result will appear in a matrix or on a map; this depends on the functional vulnerability assessment methodology. More details of the methodology of combination is provided within the report published by the Cerema for the action 3 (Cerema, 2015b).

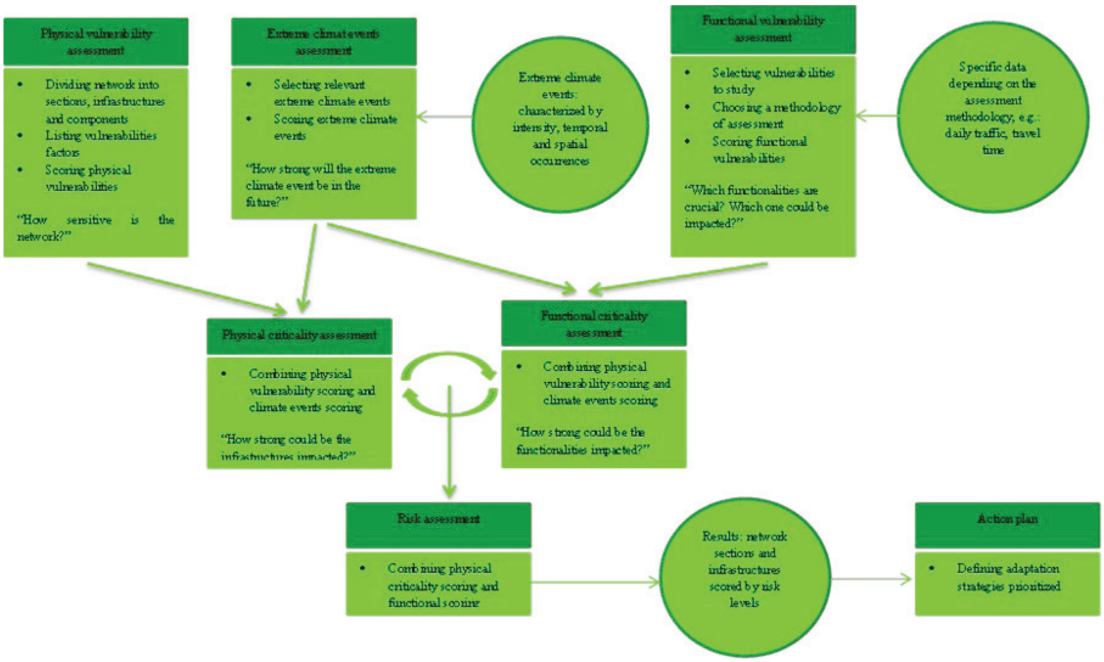

Fig. 2. Risk assessment framework.

4. Conclusion

Adaptation of transport networks and infrastructures to future standard climate conditions and to extreme events has been addressed through the actions 1, 3 and 4 of the Plan. These actions are still on-going and will continue after 2015 throughout the next French Adaptation Plan.

The complete updating of standards is conditioned by the availability of climate projections: the way forward will be to calculate the projections and then, to adapt the standards.

The methodology of risk assessment is being developed and improved thanks to feedback of pilot studies. The aim of this methodology is to provide to managers and planners tools to develop adaptation strategies with prioritized measures, to reinforce the resilience of their infrastructures and networks. The next step will be to disseminate the methodology particularly through trainings and seminars, and to establish maps of risks level for various networks types at the French scale.

This work of adaptation will be complemented by the draft of a report for the second action, aimed at understanding how climate change will impact travel demand and more especially, daily mobility.

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