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ROADAPT

Climate data requirements of National Road Authorities for the current and future climate

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CEDR Call2012: Road owners adapting to Climate Change

ROADAPT
Roads for today, adapted for tomorrow

Climate data requirements of National Road Authorities for the current and future climate

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Executive summary

Climate services include the development, provision and dissemination of climate data, information and knowledge to inform the public, researchers, decision makers (policy and practice) or other specific users. As such, climate services should involve strong partnerships with stakeholders, in this case the NRA's and those providing information and data to these NRA's. Better dissemination and increased relevance require proper knowledge of users' requirements. For this purpose, an update was made of the requirements of NRA's as presented in the RIMAROCC-project (Table 1, p. 15 in Bles et al, 2010) with the help of a literature review of former projects, a workshop and some case studies.

Which climate variables are needed by NRA's?
Table 1.1 gives an overview of the threats for road infrastructure as included in ROADAPT and the related climate variables. As expected for design/construction and maintenance climate data is considered important. For operation weather forecasts are most important.

What are important thresholds for these climate variables?
Little information could be obtained about thresholds or critical values for threats or climate variables. Thresholds may differ in time, between regions and with different construction types (age, used standards, countries). Often they are difficult to determine, since the processes behind the threats are not always fully understood (e.g. in case of landslides). The lack of information on thresholds was also the reason for switching from the first proposed tipping point method to the ROADAPT method on selection of adaptation measures and strategies for mitigation (Blied et al., 2015c).

For which time horizon are these climate variables needed and which spatial and temporal resolution is required?
For design and construction the longest time horizons are taken into account, depending on the lifetime of the asset up to 2050 and sometimes up to 2100 (see Table 2.1). For maintenance and operation mainly data for the current climate are needed and for the next 1-5 years. Sometimes information up to 2030 is requested.

Climate data with high spatial and temporal resolution is requested in many cases (see Annex 1). A spatial resolution of 1-10 km is most requested, and sometimes even of 100 m. However, climate observations and climate projections are often not available at the highest resolutions. Downscaling may help in these cases. The requested temporal resolution is related to the threats. The highest resolution is requested for extreme rainfall (minutes-hours): also short duration extreme rainfall can cause flooding in paved areas.

How are climate data used?

- There is little information on which period is used as the reference and/or to describe the current climate, although often observational data are used (or statistics based on these). Practices related to the use of reference periods differ per country and organization. Data for the future are used or it is mentioned that they should be used;
- Much of the climate data is obtained from the National Meteorological (and Hydrological) Institutes, although sometimes also other sources of climate data and information are used;
- There are some national standards on road infrastructure that indicate what climate data should be used, but hardly any international standards are available (although some results of European projects could be used as international standards). In general experiences from the past are very important, especially for operation and maintenance.

For the design and construction for a future climate, it is not possible to lean on experience only. Regularly some modification of the data for the current climate is used;

- The way of dealing with uncertainties is rather diverse. Upper/lower limits, statistics and scenarios are all used (some in combination: upper/lower scenarios). It is not clear whether the users make a distinction between different types of uncertainties (not all methods can be used for all types, as mentioned during the presentation).

Have requirements of NRA's changed over time?
The document on 'Adaptation to climate change' from CEDR (2012), gives a good overview of the main effects of climate change for road infrastructure, activities related to adaptation to climate change in a considerable number of European countries and the main projects on this subject. From the documents on international projects and national studies it is hard to determine whether the required climate variables by NRA's have changed in the past years. In most documents the (main) threats are mentioned and regularly also the related climate variables. However, in the reviewed documents hardly any new threats or climate variables have been identified compared to Table 1.1 in this report.

From inventories on users' requirements (not specifically on road infrastructure) it is known that when people start working on climate change impacts and adaptation, the requests for climate data become more detailed and that often higher spatial and temporal resolutions are requested.

How are the results of this inventory on user requirements used in ROADAPT?

- Further specification of users' requirements and use of climate data: Table 1 from RIMAROCC (Bles et al., 2010) was updated and reserved;
- Spatial and temporal resolution: in Bessembinder (2015) information is given on spatial differences and an overview is given of downscaling methods;
- Reference current climate: overview of available 'climate normals' (description of the long term averages over recent 30 year periods) in various European countries and the links to the national meteorological institutes are given in Bessembinder (2015);
- Sources of climate data: overview of the most important cross-border sources for the current and future climate is given in Bessembinder (2015). Also a few easy to access and use datasets/tools are presented (with an explanation how to use them);
- Uncertainties: In Bessembinder (2015) a separate paragraph (Par. 2.3 and 2.4) was included on the various types of uncertainties and ways to deal with them;
- Background information on climate and climate change: since many people have limited knowledge about climate (change), an additional chapter with more general information on climate (change) is added to the guidelines for the use of climate data (Bessembinder, 2015) and a chapter where many questions about climate data/information are listed with the link to the relevant paragraphs in the document or to relevant websites.

1 Introduction

Infrastructures are the backbone of our society. Citizens, companies and governments have come to rely on and expect uninterrupted availability of the road network. Extreme weather is an important factor for the reliability and safety of the road network. In the same time. it is generally understood that the climate is changing and that this will have significant effects on the road infrastructure. Since road infrastructure is vital to society, climate change calls for timely adaptation.

Although there are considerable uncertainties involved in both the projections of future climate change and related socio-economic developments and in estimations of the consequences of these changes in transportation needs, there is a constant need for decisions and development of the road transport system. As stated in the CEDR 2012 Climate Change DoRN: '*Road authorities need to evaluate the effect of Climate Change on the road network and take remedial action concerning design, construction and maintenance of the road network*.'

The ROADAPT project is part of this CEDR Call. ROADAPT[1] has an integral approach following the RIMAROCC (Risk Management for Roads in a Changing Climate) framework that was developed for ERA NET ROAD in 2010. ROADAPT aims at providing methodologies and tools enabling tailored and consistent climate data information, a good communication between climate researchers and road authorities, a preliminary and fast quick scan for estimating the climate change related risks for roads, a vulnerability assessment, a socio economic impact analysis and an action plan for adaptation with specific input from possible adaptation techniques related to geotechnics and drainage, pavements and traffic management.

Output of the ROADAPT project are guidelines that address all these topics. In the main guidelines an overview of all topics is provided. In five following parts the specific topics are addressed in detail. These five parts are:
A. Guidelines on the use of climate data for the current and future climate
B. Guidelines on the application of a QuickScan on climate change risks for roads
C. Guidelines on how to perform a detailed vulnerability assessment
D. Guidelines on how to perform a socio economic impact assessment
E. Guidelines on how to select an adaptation strategy

This report deals with part of the aim related to A (Guidelines on the use of climate data for the current and future climate). In Bessembinder (2015) guidelines are given for the use of climate data. In this report climate data requirements are further elaborated. <u>Information from this report is used to tailor the Guideline on the use of climate data to user requirements.</u> Also information from the parallel CliPDar[2] project is used in this report.

[1] ROADAPT: project title 'Roads for today, adapted for tomorrow'.
[2] CliPDaR: project title 'Design guideline for a transnational database of downscaled climate projection data for road impact models (Matulla & Namyslo, 2014).

1.1 Aim

The aim of this document is to give further specification of requirements of various specializations covered by the National Road Authorities (NRA's) related to climate data for the current and future climate for transnational road networks in Europe, compared to the RIMAROCC project.

Questions such as the following will be answered:

- Which climate data/indices are needed (any new information on the requirements compared to former projects)?
- Can thresholds for climate variables be specified above which climate related threats occur?
- For which time horizon in the future are climate data needed?
- What is the spatial resolution required?
- How are the climate data currently used in vulnerability studies related to road infrastructure?
- Have requirements for climate data changed over time?

Figure 1.1. A24 motorway in Portugal. Right: stretch between Chaves and Pedras Salgadas (A24 motorway); Left: stretch between Fortunho and Vila Real.

1.2 Climate services and users' requirements

Knowledge on users' requirements and users is fundamental for providing relevant, salient and credible Climate Services. Collecting this information is not as simple as asking users what they want. Asking users (in this case NRA's and impact researchers and consultancies) results in a list with climate variables needed, but information on e.g. the required format, the relevant thresholds, the way climate data are used, the context in which they want to use the requested information is often not obtained that easily.

The challenge of climate services[3] to society is to bridge the gap between scientific knowledge to knowledge that is usable by policy makers and infrastructure designers. A typical road-owner or road engineer in Europe will not be helped by scientific papers, but will need information such as the return times of extreme rainfall or snowfall in the current climate and possible changes in the future. A dialogue is needed to match supply and demand. In earlier projects on climate change and infrastructure and road networks this dialogue was started already.

On a national scale in Europe many climate services have been developed. The cooperation between these initiatives is not mature yet, as they are often led and financed by national governments, serving national adaption policies. There is a lot of attention for Climate Services at the national, European and international scale. Bessembinder (2015) gives an overview of the state of art of Climate Services in Europe. These initiatives seek to improve the international cooperation and develop common methodologies to serve users of climate information.

1.3 Methodology for updating users' requirements

To understand users' requirements both information about the services that users require (what do users ask for/need?) and information to better understand the requests (why do users ask for these services, how will they use the data/information?, etc.) are required. Information on what users ask for is much easier to get than information on why users ask for specific information. Information on users' requirements related to international road infrastructure is collected through:

- A workshop/dialogue organized in April 2013 (Chapter 2)[4];
- Review of documents (from recent European projects and some national inventories; Chapter 3);
- From 3 case studies in the ROADAPT project.

During the ROADAPT project a table with threats and related climate variables was constructed with the help of all partners. This table is an updated and reversed version of Table 1 in the RIMAROCC-report (Bles et al., 2010). This table can be used to select the relevant climate variables that should be included in a quick scan or more detailed study. As a result of the inventory in this report the original version of Table 1.1 was adapted a little: a few threats and relevant climate variables were added (explained in the following chapters).

[3] Climate services are limited here to climate data, information and knowledge. Information on impacts is not included in this report, however, the other partners in the ROADAPT-project provide information on (tools to determine the) impacts of climate and climate change.
[4] Information from the workshop of CliPDaR held May 6-8 2013 in Vienna was also taken into account (Matulla & Namyslo, 2013).

Table 1.1 Threats and related climate parameters, imposing risks to the road infrastructure.

Threat (main)	Threat (sub)	Climate parameter	Unit	Time resolution
Flooding of road surface (assuming no traffic is possible)	Flooding due to failure of flood defense system of rivers and canals, caused by snow melt, rainfall in catchment area, extreme wind	Temperature (in catchment area)	˚C, days T_{avg}>0 ˚C	days
		Extreme rainfall (long periods with rain in catchment area)	mm/days	days-week
		Extreme wind speed	m/s	hours-days
		Wind direction	degrees	hours-days
	Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)	Extreme rainfall events (heavy showers)	mm/h	minutes-hours
		Extreme rainfall events (long periods with rain)	mm/days	days-week
	Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges	Sea level (rise)	cm	year(s)
		Extreme wind speed(-> storm surge)	m/s	hours-days
		Wind direction (-> storm surge)	degrees	hours-days
	Flooding from snow melt (overland flow after snow melt)	Temperature	˚C, days T_{avg}>0 ˚C	days-weeks
Erosion of road embankments and foundations	Overloading of drainage systems crossing the road	Extreme rainfall events (long periods of rain)	mm/days	days-weeks
		Extreme rainfall events (heavy showers)	mm/h	minutes-hours
		Thaw (for rapid ablation of snow)	˚C	days
	Erosion of road embankments	Sea level (rise)	cm	year(s)
		Extreme wind speed(-> storm surge)	m/s	hours-days
		Wind direction (-> storm surge)	degrees	hours-days
		Extreme rainfall events (long periods of rain)	mm/days	days-weeks
		Extreme rainfall events (heavy showers)	mm/h	minutes-hours
	Bridge scour	Sea level (rise)	cm	year(s)
		Extreme wind speed(-> storm surge)	m/s	hours-days
		Wind direction (-> storm surge)	degrees	hours-days
		Extreme rainfall events (long periods of rain)	mm/days	days-weeks
		Extreme rainfall events (heavy showers)	mm/h	minutes-hours
Landslips and avalanches	External slides, ground subsidence, affecting the road	Extreme rainfall events (long periods of rain)	mm/days	days-weeks
		Extreme rainfall events (heavy showers)	mm/h	minutes-hours
		Drought (consecutive dry days)	consecutive days	multiple days-months
	Slides of the road embankment	Extreme rainfall events (long periods of rain)	mm/days	days-weeks
		Extreme rainfall events (heavy showers)	mm/h	minutes-hours
		Drought (consecutive dry days)	consecutive days	multiple days-months
	Debris flow	Extreme rainfall events (heavy showers)	mm/h	minutes-hours
	Rock fall	Extreme rainfall events (long periods of rain)	mm/days	days-weeks
		Extreme rainfall events (heavy showers)	mm/h	minutes-hours

Table 1.1 (continued)Threats and related climate parameters, imposing risks to the road infrastructure.

Landslips and avalanches	Rock fall	Frost-thaw cycles (nr. of days with temperature zero crossings)	nr. of days	days
	Snow avalanches	Snow fall	mm/day	day-weeks
		Frost-thaw cycles (nr. of days with temperature zero crossings)	nr. of days	days
		Temperature	˚C	days
Loss of road structure integrity	Impact on soil moisture levels (increase of water table), affecting the structural integrity of roads, bridges and tunnels	Seasonal and annual average rainfall	mm/season, mm/y	season-year
		Sea level (rise)	cm	year(s)
		Extreme wind speed(-> storm surge)	m/s	hours-days
		Wind direction (-> storm surge)	degrees	hours-days
	Weakening of the road embankment and road foundation by standing water	Seasonal and annual average rainfall	mm/season, mm/y	season-year
	(Unequal) settlements of roads by consolidation	Drought (consecutive dry days)	consecutive days	multiple days-months
	Instability / subsidence of roads by thawing of permafrost	Frost-thaw cycles (nr. of days with temperature zero crossings)	nr. of days	days
	Uplift of tunnels or light weight construction materials by increasing water table levels	Seasonal and annual average rainfall	mm/season, mm/y	season-year
		Sea level (rise)	cm	year(s)
		Extreme wind speed(-> storm surge)	m/s	hours-days
		Wind direction (-> storm surge)	degrees	hours-days
		Extreme rainfall events (long periods of rain)	mm/days	days-weeks
Loss of pavement integrity	Cracking, rutting, embrittlement	Maximum and minimum diurnal temperature	˚C	days
		Nr. of consecutive hot days (heat waves)	consecutive days	days
	Frost heave	Frost days	˚C, nr. of days	days
	Aggregate loss and detachment of pavement layers	Frost days	˚C, nr. of days	days
	Cracking due to weakening of the road base by thaw	Frost-thaw cycles (number of days with temperature zero crossings)	nr. of days	days
	Thermal expansion of pavements	Maximum and minimum diurnal temperature	˚C	days
		Nr. of consecutive hot days (heat waves)	consecutive days	days
	Decreased utility of (unimproved) roads that rely on frozen ground	Frost-thaw cycles (number of days with temperature zero crossings)	nr. of days	days
Loss of driving ability due to extreme weather events	Reduced visibility	Fog days	nr. of days	day
	Reduced visibility during snowfall, heavy rain including splash and spray	Snow fall or rainfall	mm/h, mm/day	minutes-day
	Reduced vehicle control	Extreme wind speed (worst gales)	m/s	hours-day

Table 1.1 (continued)Threats and related climate parameters, imposing risks to the road infrastructure.

Loss of driving ability due to extreme weather events	Reduced vehicle control	Extreme wind speed (wind gusts)	m/s	seconds-minutes
Loss of driving ability due to extreme weather events	Decrease in skid resistance on pavements from slight rain after a dry period	Drought (consecutive dry days)	consecutive days	multiple days-months
Loss of driving ability due to extreme weather events	Flooding of road surface due to low capacity of storm water runoff	Extreme rainfall events (heavy showers)	mm/h	minutes-hours
Loss of driving ability due to extreme weather events	Aquaplaning in ruts due to precipitation on the road, splash and spray	Extreme rainfall events (heavy showers)	mm/h	minutes-hours
Loss of driving ability due to extreme weather events	Decrease in skid resistance on pavements from migration of liquid bitumen	Maximum and minimum diurnal temperature	˚C	days
Loss of driving ability due to extreme weather events	Decrease in skid resistance on pavements from migration of liquid bitumen	Nr. of consecutive hot days (heat waves)	consecutive days	days
Loss of driving ability due to extreme weather events	Icing and snow	Snowfall	nr. of days, mm/d	days
Loss of driving ability due to extreme weather events	Icing and snow	Hail	nr. of days, mm/d	days
Loss of driving ability due to extreme weather events	Icing and snow	Frost days and rainfall	nr. of days, mm/d	days
Reduced ability for maintenance	Reduced snow removal planability	Snowfall	mm/day	day-season
Reduced ability for maintenance	Reduced ice removal planability	Frost	nr. of days	days
Reduced ability for maintenance	Impact on shoulder maintenance: increased vegetative growth	Temperature	˚C	days
Reduced ability for maintenance	Impact on road works: decreased time window for paving	Maximum and minimum diurnal temperature	˚C	days
Reduced ability for maintenance	Impact on road works: decreased time window for paving	Nr. of consecutive hot days (heat waves)	consecutive days	days
Pollution aside the road after incapacity of storm water runoff system of the road		Extreme rainfall events (heavy showers)	mm/h	minutes-hours
Susceptibility to wildfires that threaten the transportation infrastructure directly		Drought (consecutive dry days)	consecutive days	multiple days-months
Damage to signs, lighting fixtures, pylons, canopies, noise barriers and supports		Extreme wind speed (worst gales)	m/s	hours-day
Damage to signs, lighting fixtures, pylons, canopies, noise barriers and supports		Extreme wind speed (wind gusts)	m/s	seconds-minutes
Damage to energy supply, communication networks (e.g. pylons) and/or matrix boards by wind, snow, heavy rainfall and/or lightning		Extreme wind speed (worst gales)	m/s	hours-day
Damage to energy supply, communication networks (e.g. pylons) and/or matrix boards by wind, snow, heavy rainfall and/or lightning		Extreme wind speed (wind gusts)	m/s	seconds-minutes
Damage to energy supply, communication networks (e.g. pylons) and/or matrix boards by wind, snow, heavy rainfall and/or lightning		Snowfall	mm/day	days
Damage to energy supply, communication networks (e.g. pylons) and/or matrix boards by wind, snow, heavy rainfall and/or lightning		Extreme rainfall events (heavy showers)	mm/h	minutes-hours
Damage to energy supply, communication networks (e.g. pylons) and/or matrix boards by wind, snow, heavy rainfall and/or lightning		Extreme rainfall events (long periods of rain)	mm/day	days-weeks
Damage to energy supply, communication networks (e.g. pylons) and/or matrix boards by wind, snow, heavy rainfall and/or lightning		Lightning	nr. of discharges	hour to days
Trees, wind mills, noise barriers, trucks falling on the road		Extreme wind speed (worst gales)	m/s	hours-day
Trees, wind mills, noise barriers, trucks falling on the road		Extreme wind speed (wind gusts)	m/s	seconds-minutes

2 Workshop on climate data requirements for National Road Authorities and case studies

In April 2013 a workshop was held with representatives from some NRA's and from research institutes working on road infrastructure. The workshop took place in Delft, The Netherlands, in combination with other ROADAPT workshops. The aim of the workshop on users' requirements related to climate data was:

- To give the participants some information on the availability of climate data for the current and future climate in Europe and the possibilities and limitations of the use of climate data (this information is included in the guideline on the use of climate data; Bessembinder, 2015);
- To check whether requirements have changed;
- To further specify requirements;
- To obtain some information on the users and possible differences between countries.

Information from this workshop was used, among others, to see whether more or different climate variables, information, methods, etc. should be presented in ROADAPT.

In an interactive way further specification was obtained of the climate data requirements of NRA's and those providing information on climate change to the NRA's and about the background of these requirements. Several questions were used during the workshop to get more information from the participants. The participants were asked to fill in tables: the input from the participants is presented in Annex 1 and the general results are discussed below in Par. 2.1 to 2.9.

From May 6-8, 2013 also a user's workshop was held in Vienna by the parallel CliPDaR project. It is checked whether other threats were identified during that workshop or whether other relevant climate variables for certain treats were identified (Par. 2.10).

Par. 2.11 describes some experiences from the ROADAPT case studies. In Par. 2.12 the conclusions on the workshops are presented and it is indicated how this information on user requirements was used in ROADAPT.

2.1 Are relevant climate variables missing?

The first question to the participants during the workshop was to indicate whether certain climate variables were missing in the RIMAROCC project. This information is needed to see whether the requirements have changed or whether important climate variables were missing in RIMAROCC.

Since many participants[5] did not know exactly what was in the RIMAROCC table, during the workshop this question was interpreted as 'what are relevant or the most important climate variables?' This gave a confirmation of what was already included in RIMAROCC. Most of the climate variables or climate information mentioned in this list were already in Table 1 of the RIMAROCC report (Bles et al., 2010). At this stage of the workshop, already some further specification was given for some climate variables/information (e.g. for extreme events).

[5] The participants at the workshop were from the following countries: Denmark, France, Germany, Netherlands, Norway and Sweden.

2.2 Further specification of requirements per time horizon

The second question focused on further specification of the requirements per time horizon. For that purpose we made a distinction between:

- Design/construction;
- Maintenance;
- Operation[6].

These categories may have different requirements, different time horizons, etc.

Table A1 in Annex 1 presents the input from the participants on further specification of what information on climate variables is needed. Also some distinction between the various types of activities (and related time horizons) is given. As was already clear form the first question in the workshop, people are most interested in precipitation and extremes. As expected, especially for design and construction information on longer time horizons is requested. Statistical information (probabilities, exceedance frequencies) is most often asked for, but also time series as input for impact assessments.

The above gives some further and useful information on requirements, however, from experience we know that these requirements are often best specified and adapted when working together in projects. Therefore, it would be useful to collect experiences from projects where climate data are actually used in impact, adaptation and vulnerability assessments (what was requested, what was actually used and how were the data used?).

2.3 Which spatial and temporal resolutions needed?

There are limits to the resolution that can be delivered for temporal and spatial data about climate. Many impact models use a specific resolution. Annex 1 Table A2 indicates the required or desired spatial and temporal resolutions for specific climate variables and/or threats.

As can be seen, often high spatial resolutions are requested. Climate observations and climate model data generally do not have such high spatial resolutions (for observations a resolution of about 10 * 10 km is already very high[7]; the spatial resolution of the newest regional climate models is now about 10 * 10 km). This means that spatial downscaling is needed or at least some information on spatial differences: some climate variables show much larger spatial differences at a scale of 100 m to 10 km than others (see also Bessembinder, 2015).

The temporal resolution requested in Table A2 differs considerably and is related to the relevant process that causes the threat. Especially for precipitation (and wind) high temporal resolutions are requested (hours to minutes). Often at least some information is available from observations, but climate models provide especially information on daily basis (or coarser scales). Climate models can also provide information on hourly basis, however, it is more difficult to determine the quality or skill[8] of this information, since far less observational data are available at this temporal scale to determine the skill of climate models for this

[6] This requires often mainly weather information, which is not the aim of this project, but none the less it was included since for the users there is often no clear distinction between weather and climate information.
[7] Often the spatial resolution for precipitation data is highest.
[8] See also the Guideline on the use of climate data (Bessembinder, 2015) for the definition of skill of climate models.

temporal scale. This means that also some temporal downscaling of information for the future may be needed.

2.4 Which climate information used for the current and the future climate?

The next question was about the use of climate data and information: do people use climate data for the current and future climate? And which data are used? The answers are presented in Annex 1.

In general, it is recognized that climate information is needed for the future, especially for design and construction. Many use the same approach or same type of data for the current and future climate (e.g. rain intensity curves, 'design' showers), although sometimes it is difficult to generate the same type of information for the future: as explained in Par. 2.3, information on the changes of extreme precipitation per hour or per minute often cannot be obtained directly from climate model simulations. Information on the exact way in which climate data are used currently is often lacking. This makes it more difficult to supply tailored data within ROADAPT. As indicated in Par. 2.2 it would be useful to collect experiences from projects where climate data are actually used in impact, adaptation and vulnerability assessments (what was requested, what was actually used and how were the data used?).

2.5 Importance of climate extremes for design/construction, maintenance and operation of roads?

With this question we tried to get some information on the importance of climate data (extremes) compared to other often socio-economic aspects. The relative importance will affect the time and money available or invested in the analysis of climate data. The participants were asked to score the relative importance. The results are shown in Annex 1.

From Table A4 in Annex 1 it can be concluded that the importance of climate data differs enormously. The reason for these differences were not discussed during the workshop, however, the impact or risk to extreme weather is also related, among others, to the intensity of use of a road. Also, often the socio economic developments in the future (especially the nearer future) are mentioned as being even more uncertain and important than climate change.

2.6 Which period used to describe the current climate?

Hardly any information was given on which period is used to describe the current climate or which period is used as a reference for climate change. During the workshop there was a lot of discussion on which reference period to use: should the minimum standard of the World Meteorological Organization be used (now 1961-1990, but from 2021 on it will be 1991-2020) or should the most recent 30 years be used (countries are also encouraged by WMO to give each 10 years a new description of the climate based on the past 30 years)? It was clear from the discussions that the participants often weren't aware that different reference periods could be used in cross-border projects and that more information is needed on this.

2.7 Sources of climate data and information?

It is also useful to know where the NRA's or organizations working for NRA's get their climate data and information from (e.g. commercial provider, National Meteorological Institute (NMI), consultancy company). This may affect the access to climate data and information, the format in which they get the information or even the interpretation of the available data and information.

Table A5 in Annex 1 shows that climate information is often, but not exclusively, obtained from the national meteorological institutes. Sometimes this may also include assistance from these institutes in the use of the climate data, but from the workshop it did not become clear how often this is the case. More and more climate data can be downloaded now from websites without direct contact with climate scientists or providers. People often find it difficult to get overview of what datasets are available and what are the advantages and disadvantages of certain datasets. From experiences in the Netherlands we know that this happens often. Only in case of problems, the meteorological institutes are consulted personally.

2.8 The use of national or international standards

The next question was related to the use of extremes. How do the participants determine or know which extremes to use for design/construction, maintenance and operation? Are these based on national or international standards or on experiences related to vulnerability? The answers to this question are presented in Annex 1 Table A6.

Some national standards including the use on information about climate change are available, however, these are not available on the European level.

2.9 Dealing with uncertainties in climate data

The last question in the workshop was on dealing with uncertainties in climate data (statistics, probabilities, 1 or more scenarios, etc.). Inevitably uncertainties are mentioned when talking about climate change. For the provider of climate data and information it is useful to know how the users deal with the various types of uncertainties in order to supply useful information.

As can be seen in Table A7 in Annex 1 most organizations have their own way of dealing with uncertainties. From the workshop we got the idea that most do not make a clear distinction between the various types of uncertainties.

2.10 CliPDaR users workshop

The CliPDaR user's workshop was held from May 6 to 8, 2013 in Vienna and is described in Matulla & Namyslo (2013). Several threats and the relevant climate variables for these threats were discussed. DWD and ZAMG, the partners in CliPDaR, both come from countries with large mountainous areas, therefore a lot of attention was paid to threats related to these areas. KNMI, the national Meteorological Institute involved in ROADAPT has little experience in mountainous areas, therefore it is interesting to see whether the CliPDaR workshop resulted in somewhat different information on threats and related climate variables.

Analysis of the CliPDaR workshop report resulted in the following additional information (many of the threats and related climate variables are the same as mentioned in ROADAPT):

- For landslides also thaw-freeze cycles are mentioned as relevant climate variable[9];
- For erosion of road embankments also rapid ablation of snow and heavy precipitation following a hot and dry period are mentioned as relevant climate variable[9];
- As additional threat the destabilization of retaining walls on hills is mentioned. The failure can be caused by heavy precipitation or snowfall and snow melt[10];
- Another additional threat is the destabilization of noise walls by erosion due to heavy precipitation[10];
- Snow drift due to wind resulting in blocking the road (loss of driving ability) is also mentioned as a threat[11].

As can be seen from the above list, there are only a small number of additional threats or relevant climate variables for certain threats and the additional information is related in most cases to conditions that happen more often in mountainous areas. In CliPDaR the relevant climate variables or combinations of relevant climate variables are called Climatological Indices (CI) and they are presented in their Cause-Effect-Matrix.

The CliPDaR report also gives some information on the availability of guidelines:

- There are some guidelines for maintenance in Germany, but they do not include climate change (also not very relevant for maintenance);
- There are also some construction guidelines which require information on wind in Germany. Again no climate change is included explicitly;
- In several countries vulnerability analyses have been elaborated including possible effects of climate change (in Denmark and the Netherlands: so-called ‘blue spots’ projects);
- And there are some cross border contacts (e.g. between France and Germany) for vulnerability analyses.

The Strategic European Road Research Program V (SERP V; FEHRL, 2011) focuses on how to design, built, operate and maintain roads in a flexible way in the coming century, resulting in a ‘Forever Open Road’.

2.11 ROADAPT case studies

Within the ROADAPT project 3 case studies were elaborated:

- A24 Motorway in Northern Portugal (Ennesser, 2015; supply of climate data is described in Chapter 3 in Bessembinder (2015));
- Rotterdam-Ruhr corridor (Dutch part; Bles & Woning, 2015b);
- Öresund region in Sweden (Falemo & Blied, 2015).

Below some experiences are described:

- Table 1.1 is a useful tool for translating threats in relevant climate variables for climate scientists. Climate scientists may have some idea of which climate variables are relevant for which threats, but they do not always know all relevant variables or the relevant

[9] Added in a later stage to Table 1.1 in this report.
[10] Although not explicitly mentioned in Table 1.1 it can be considered part of the threat “Land slips and avalanches”.
[11] Although not explicitly mentioned in Table 1.1 it can be considered part of the threat “Loss of driving ability”.

temporal scales. Therefore, this tables makes it easier to provide relevant climate information;

- It is often not easy to get access to local/national data and find information on e.g. statistics on extremes. The language may be a problem (although Google translate is of great help; e.g. used to get access to some background documents for the Öresund region), but often also climate data and statistics are not freely available. In these cases the help of a local expert to find out what is available can be useful (e.g. check with local expert on the existence of new climate scenarios for Portugal). For a quick scan the use of the ECA&D[12] website for information on the current climate may often be sufficient. Although this depends largely on the availability of data in ECA&D (very limited for northern Portugal and Denmark/Sweden);
- Visual information in the form of maps with e.g. trends, spatial differences in climate variables (e.g. as generated with ECA&D) are often more powerful to transfer information on the current and future climate than tables with information. Therefore, they are useful for quick scans and discussions with stakeholders;
- For a quick scan often rather qualitative information on climate is sufficient (although detailed information is appreciated). It is more important to get an idea whether the occurrence of the threats may increase, decrease or remain the same;
- The level of knowledge about climate and climate change differs considerably between stakeholders and it is often difficult for stakeholders to distinguish between climate change and natural variability of climate. This may also affect the interpretation of information on climate (recent climate extremes are often attributed to climate change, whereas it may also be an expression of natural variability). It can be important to check what is the knowledge of the stakeholders (including those doing the impact, adaptation and/or vulnerability analyses) on climate and climate change. This may avoid misunderstandings;
- Questions of stakeholders are often related to recent extreme events (e.g. in the ROADAPT project questions on the recent cold winters). This is also the case in most other sectors. These recent extreme events can be used to explain what is natural variability of the climate and/or they can be used to explain what climate change may look like in the future (e.g. the warm summer of 2003 may become more or less normal in the future).
- Also recent publications that got much attention can result in many questions and/or discussions. In the Rotterdam-Ruhr case study apparently a publication or presentation on the effects of climate change stated that the long term average number of days with thaw-freeze would increase in the coming decades in the Netherlands and only after about 2050-2060 it would decrease again[13]. Calculations with the most recent climate scenarios by KNMI for air temperature indicated that this seems very unlikely, although there may be considerable year-to-year variation. These contrary results led to much discussion;
- Hardly ever explicit distinction is made between the various types of uncertainties in climate data. It is often not discussed (in advance) with climate scientists how one can deal with uncertainties for the future climate.

[12] European Climate Assessment & Database: www.ecad.eu.
[13] The publication/presentation could not be found to check on which information this was based. Apparently the results seemed plausible to the stakeholders, maybe due to the recent cold winters.

2.12 Conclusions workshops

The workshops revealed the following:

- Most of the mentioned climate variables were already directly or indirectly in the RIMAROCC report. The answers gave a further specification of what is needed (especially extreme events and probabilities, and derived variables such as flooding, storm surge, ground water tables). Table 1 in the RIMAROCC report was reversed and supplemented (Table 1.1 in this report and Table 3.1 in Bessembinder (2015)). The table now starts with the threats, since the NRA's start with the threats and not with climate variables. The CliPDaR user's workshop revealed a few additional relevant climate variables and threats that were included in this table;
- As expected for design/construction much longer time horizons are taken into account and for maintenance mainly data up to 2030 are needed. Extreme precipitation is most often mentioned;
- Climate data with high spatial and temporal resolution is requested in many cases, for the future and to a lesser extent for the current climate. It is difficult to deliver the highest requested resolutions, since there are a lot of uncertainties (see Bessembinder, 2015)). It is not clear whether this high resolution is absolutely necessary or that a coarser resolution with some indication of spatial differences at the requested resolution is also sufficient;
- There is little information on which period is used as the reference and/or to describe the current climate, although often observational data are used (or statistics based on these). During the workshop there was a lot of discussion on which reference period to use: should we use the minimum standard of the WMO (now 1961-1990) or the most recent 30 years. Practices related to the use of reference periods differ per country and organization. It became clear that at least explanation of the different practices is needed and maybe a recommendation on a common reference period can be given for European countries (Bessembinder, 2015). Data for the future are used or it is mentioned that they should be used;
- As expected for design/construction climate data for the future is considered important, and especially extreme precipitation is often mentioned. For operation weather forecasts are more important (although some mix the terms weather and climate);
- Much of the climate data is obtained from the National Meteorological (and Hydrological) Institutes, however sometimes also other sources of climate data and information are used. It would be interesting to see why other providers than the NM(H)I are used: is it for the processing and/or interpretation of the climate data for the current and future climate?
- There are some national standards on which climate data should be used, but hardly any international standards (although some results of European projects could be used as international standards). In general, experiences from the past are very important, especially for operation and maintenance. For the design and construction for a future climate, it is not possible to lean on experience only. Regularly some modification of the data for the current climate is used;
- The way of dealing with uncertainties is rather diverse. Upper/lower limits, statistics and scenarios are all used (some in combination: upper/lower scenarios). It is not clear whether the users make a distinction between different types of uncertainties (not all methods can be used for all types, as mentioned during the presentation). Some more information on this is needed, and probably special attention should be given to this in the guidelines on the use of climate data (Bessembinder, 2015).

From the workshops it could not be concluded that user's requirements have changed in the past years[14]. Probably it is also very difficult to detect this. Regular contact with the users (NRA's and organizations doing studies for the NRA's) is needed to check whether requirements change in the future. The regular contact with the users is also important to understand how the users work with climate data and for the users to understand what climate information can and cannot be delivered to them. Case studies, as executed in the ROADAPT project, also help to get more mutual understanding.

How were the results of the workshop and case studies used in the ROADAPT work package on Climate Services?

- Further specification of users' requirements and use of climate data: Table 1 from RIMAROCC (Bles et al., 2010) was updated and reserved;
- Spatial and temporal resolution: in Bessembinder (2015) information is given on spatial differences and an overview is given of downscaling methods;
- Reference current climate: overview of available 'climate normals' (description of the long term averages over recent 30 year periods) in various European countries and the links to the national meteorological institutes are given in Bessembinder (2015);
- Sources of climate data: overview of the most important cross-border sources for the current and future climate is given in Bessembinder (2015). Also a few easy to access and use datasets/tools are presented (with an explanation how to use them);
- Uncertainties: In Bessembinder (2015) a separate paragraph (Par. 2.3 and 2.4) was included on the various types of uncertainties and ways to deal with them;
- During the ROADAPT workshop in Delft also many more general questions were posed on weather, climate, climate change and extreme weather events. Because of these questions an additional chapter with more general information on climate and climate change is added to the guidelines for the use of climate data (Bessembinder, 2015). The workshops delivered useful information on users requirements, the type of questions the NRA's are dealing with and the available background knowledge of the participants. In Chapter 6 of Bessembinder (2015) also many questions about climate data/information are listed with the link to the relevant paragraphs in the document or to relevant websites.

[14] We refer there to the required climate variables/parameters. Standards may have changed in the past decades as the result of new research or new climate scenarios. This is e.g. the case in the Netherlands for storm water run-off, where the rainfall intensity curve has been adjusted for 2050 (+27%).

3 Review of literature on climate data requirements

In order to get more information on climate data and information requirements, several documents from former projects were consulted. In the following paragraphs a summary is given of the information collected related to climate data. Documents for the EU, CEDR, European projects and some information from the Netherlands are consulted. Among others, the projects form the ERANET ROAD programme (Road Owners Getting to Grips with Climate Change) are included (IRWIN, P2R2C2, SWAMP). The RIMAROCC project (Risk Management for Roads in a Changing Climate) also belonged to this research programme, but it is not discussed separately in this Chapter, since ROADAPT builds explicitly on the results of this project. Table 1.1 in this report is an conversion of Table 1 in the RIMAROCC guideline (Bles et al., 2010), now putting the threats in the first column.

In the sub-paragraphs below conclusions on additional threats and/or climate variables identified are presented in italics.

3.1 EU-commission documents on transport and infrastructure

The European Commission's White Paper of 2009 '*A sustainable future for transport'* states that: 'Transport itself will suffer from the effects of climate change and will necessitate adaptation measures. Global warming resulting in a rising sea level will amplify the vulnerability of coastal infrastructure, including ports. Extreme weather would affect the safety of all modes. Droughts and floods will pose problems for inland waterways.' (EU, 2009). The white paper from 2011 (EU, 2011) mentions 'Ensure that EU-funded transport infrastructure takes into account energy efficiency needs and climate change challenges (climate resilience of the overall infrastructure, refuelling/recharging stations for clean vehicles, choice of construction materials…)'.

These documents do not give explicit information on threats and/or climate data requirements for the transport sector.

The supplement to the EU Adaptation strategy (EU, 2013a) does give more explicit information on weather/climate related risks and related climate parameters. However, no new risks compared to Table 1.1. in this report were found. EU (2013b) states that 'Main threats to infrastructure assets include damage or destruction caused by extreme weather events, which climate change may exacerbate; coastal flooding and inundation from sea level rise; changes in patterns of water availability; and effects of higher temperature on operating costs, including effects in temperate and/or permafrost. Some infrastructure may not be affected directly but be unable to operate if physical access or services to it (such as electricity and ICT) are disrupted.'

This last point on indirect impacts of extreme weather is not treated in ROADAPT. It is outside de scope of ROADAPT.

The report of EU (2013b) recognizes that 'Design thresholds which are built into infrastructure project designs may be breached more frequently in a future changing climate. A changing climate may result in threshold failures once considered exceptional but acceptable, becoming unexceptional (i.e. normal) and unacceptable.' 'To achieve sector- and location specific climate resilience, there is thus a need for a thorough and coherent assessment of local climate impacts – based on historical records, but also including projections on future climatic conditions.' Several activities are mentioned to promote the inclusion of climate change information in infrastructure planning and retrofitting:

- 'The proposal for the new TEN-T Guidelines includes climate resilience, in particular under article 41: during infrastructure planning due consideration shall be given to risk assessments and adaptation measures adequately improving the resilience to climate change.' (Guidelines for the development of the trans-European transport network, COM(2011) 650 final/2 of 19/12/2011);
- The Commission has asked CEN (European Committee for Standardisation) to prepare a proposal for how to incorporate climate change and extreme weather events in the Eurocodes;
- 'Practical Guidance for Integrating Climate Change and Biodiversity into Environmental Impact Assessment (EIA) Procedures' is under way, aiming at supporting EU Member States, its administration, public and private authorities and planning bodies;
- European Commission (2012), Guidelines for Project Managers: Making vulnerable investments climate resilient, conducted by Acclimatise and COWI A/S, contract no. 071303/2011/610951/SER/CLIMA.C3.

At the moment hardly any threshold or critical values for climate variables related to guidelines are available. When these may become in the future, maps, trends, statistics, etc. can be prepared for these specific values.

3.2 CEDR (2012): Adaptation to climate change

Chapter 1 in CEDR (2012) summarizes the main effects of climate change on the road network as follows:

- More flooding and erosion: a challenge for drainage systems and erosion protection and for the design and maintenance of culverts and bridges;
- Landslides and avalanches: occurring more frequently, at new locations and with a higher share of 'wet' landslide types, such as slush avalanches and debris flow;
- Droughts and high summer temperatures may pose problems for asphalt surfacing, due to softening, but also for run-off conditions, due to lower permeability. Risk of wildfires may also increase in the southernmost regions;
- Deterioration of roads and pavements: as expressed by service life and rutting, mostly in cases where drainage is insufficient;
- Effects of sea-level rise on coastal stability and importance of ensuring sufficient elevation for roads, quays and bridges, as well as entrance levels for sub-sea tunnels;
- Heavy snowfall in mountain areas of northern Europe causing trouble for winter maintenance and operation under difficult conditions;
- The need for better risk management and efficient procedures for initiating remedial actions after a weather-related event occurs, due to the fact that existing protective measures may not be sufficient and that the planning of remedial measures requires time.

All these effects can be recognized in all phases of road management: planning, design, construction, maintenance, and operation. Table 2 and Appendix 1 in CEDR (2012) give the results from individual country surveys on the assessment of the probability of effects and severity of consequences due to changes in climate parameters.

This list does not include other threats for road infrastructure than originally mentioned in Table 1.1 of this report, except that it mentions pollution as a result of heavy rainfall/flooding.

Chapter 2 indicates some possible routes towards adaptation to climate change. The measures are divided into working procedures from planning to operation. Climate change will require adaptation of design guidelines in order to ensure sufficient drainage capacity and erosion protection, define adequate quality requirements for road construction materials, manage landslide risks, and implement measures to ensure protection of the environment. Construction contracts that consider climate change are important in order to avoid some of the problems that could occur during maintenance and operation.

Chapter 2 also mentions that 'maintenance and operation of the existing road network is where most of the adaptation work needs to be done. This includes risk assessment, by identifying vulnerable assets and potential risks, and risk management related to weather-related events, including both preventive measures and emergency plans. Taking care of maintenance backlogs is an important part of adaptation to climate change and is also beneficial for other reasons. In mountain areas and in northern countries, it is necessary to prepare for harsher winter conditions[15]. Traffic management under difficult weather conditions needs attention, including communication of risks, re-routing, and use of good monitoring systems for traffic control. Contracts for maintenance and operation need to be revised to ensure that adequate account is taken of climate conditions.' Figure 3.1 shows the relation between service life and climate change.

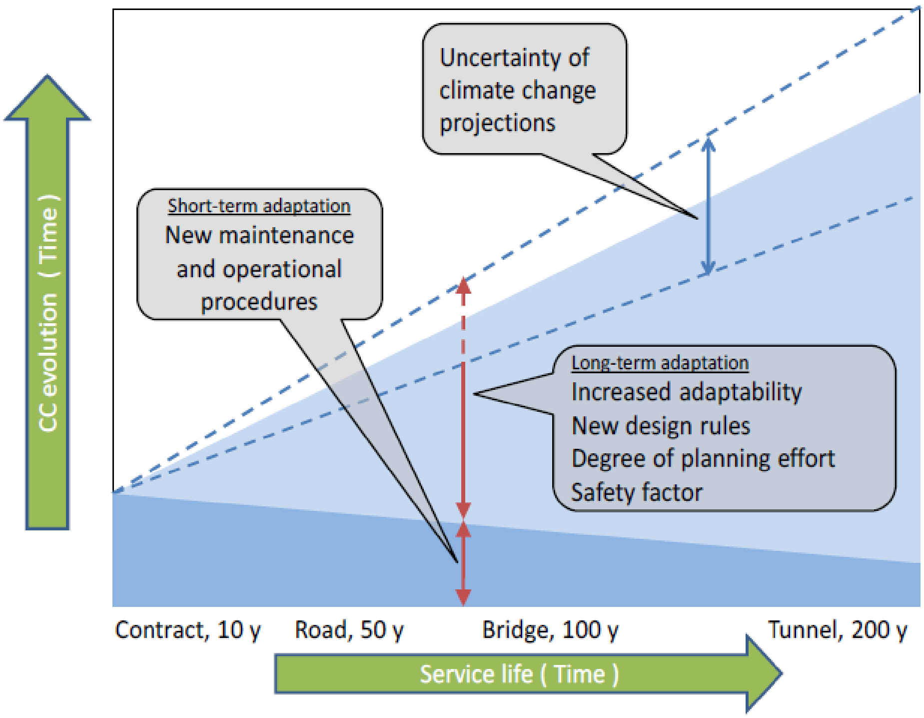

Figure 3.1 Service life, climate change evolution and short-term and long-term adaptation measures for maintaining the acceptable risk level (Figure 3 in CEDR, 2012).

If roads (including the area around them) are constructed for their expected life time including good estimates of natural variability of the current climate and possible changes in climate during their life time, adaptation related to maintenance and operation can be limited.

[15] It is not clear to what aspects of climate this is referring. Due to some relatively cold winters many thought that winter could also become colder. However, there is no clear indication that this will happen (Bessembinder, 2015a Chapter 6).

However, in many cases natural variability of the current climate is underestimated and climate change is not taken into account. As indicated in Bessembinder (2015) significant climate change cannot be detected within 5-10 years, often the period for which maintenance and operation contracts are defined.

3.3 IRWIN

The main objective of the project IRWIN - Improved local winter index to assess maintenance needs and adaptation costs in climate change scenarios – was to develop an improved winter road index capable of assessing the implications of climate change in various weather parameters and also related road maintenance actions.

According to Saarikivi et al., (2009) the factors that need to be taken into account to see whether there will be a potential change in maintenance activities for a Road related Winter Index are:

- *Ice:* It is common to use temperature falls from positive to negative degrees to indicate the risk of ice formation and the need for salting operations;
- *Precipitation* in the form of snow or water: Types include direct snowfall, with air temperatures below 0 ˚C, melting snow, or drifting snow when the snowfall occurs with strong winds. Rain, especially intense rain, may influence road safety by decreasing visibility and by causing aquaplaning. Super cooled rainwater or rains preceded by cold weather are hazardous as well since they may cause ice on the roads;
- *Wind:* Strong winds may force vehicles off the roads or in unwanted directions. Fallen trees or flying materials such as tree branches or litter may be troublesome to drivers. Winds may also create road blocks from drifting snow.

The threats mentioned above were also in the original version of Table 1.1 of this report.

Table 3.1 Calculated indices within the IRWIN project (Saarikivi et al., 2009).

Index 1	Number of events when the amount of snow was more than 1mm during 4 hours Temperature was between -3 to +1°C Wind velocity was between 0-7 m/s
Index 2	Number of events when the amount of snow was more than 1mm during 4 hours Temperature was between -3 to + 1°C Wind velocity was between 7-14 m/s
Index 3	Number of events when the amount of snow was more than 1mm during 4 hours Temperature was between -3 to + 1°C Wind velocity was more than 14 m/s
Index 4	Number of events when the amount of snow was more than 1mm during 4 hours Temperature was less than -3°C Wind velocity was between 0-7 m/s
Index 5	Number of events when the amount of snow was more than 1mm during 4 hours Temperature was less than -3°C Wind velocity was between 7-14 m/s
Index 6	Number of events when the amount of snow was more than 1mm during 4 hours Temperature was less than -3°C Wind velocity was more than 14 m/s
Index 7	Number of events when it was or had been raining and the surface temperature was less than 0,5°C
Index 8	Number of events when the surface temperature was between -6°C and 0°C during 4 hours and the dew point was larger than the surface temperature
Index 9	Number of events when the surface temperature shifts from +1°C to -1°C

3.4 P2R2C2

The final report on the P2R2C2-project (Pavement Performance & Remediation Requirements following Climate Change) mentions the effects on pavements as described in Table 3.2.

The report does not present much additional threats as compared to Table 1.1 in this report. The additional threats mentioned are:

- *Expansion of joints in concrete pavement (thermal expansion of pavements is mentioned in Table 1.1. and could include this too)[16];*
- *Increased vegetative growth[17].*

Table 3.2 Conclusion on the effects on pavements in a changing climate (Source: Dawson & Carrera, 2010)

Implication	Where significant	Effects
Change in the annual maximum temperature	Western Central Europe	Increased rutting deformation Expansion of joints in concrete pavements & at bridge decks
Change in the annual cold sum	Nordic Countries, Baltic states	Reduced frost penetration, a positive effect Bearing capacity reduction in winter-time affecting truck transport
Change in the annual heat sum	Mountains, France, S. Germany, Slovakia	Deformations on bitumen-paved roads, increased vegetative growth and indirect erosion risk
Change in number of freeze-thaw cycles	Northern Europe	Lapland: an increase in these cycles will be negative with regards to length of fully frozen period, but positive with respect to length of spring thaw and length of fully-thawed period; other regions positive effect
Change in the annual precipitation	North-western Atlantic coastal areas and Nordic / Baltic states	A largely neutral effect for water tables because increased rainfall will be offset by increased proportion running-off, except in locales prone to flooding
	All areas	Stripping of asphalt may increase following storm events and in the presence of traffic loading More rapid decay, by base and subgrade destabilization) of cracked pavements due to greater water availability during storm events, with washouts due to temporarily overcharged drainage systems. Otherwise, somewhat positive effect as water tables drop due to greater evaporation (due to higher average temperatures), greater run-off and less infiltration (because precipitation occurs in more intense, but less frequent, events)
	Local low spots	Accumulated run-off in intense rainfall events could lead to more flooding and locally raised water tables
Sea level rise	Roads at low level by sea	Greater risk of flooding and salt intrusion

The report indicates that the 'life cycle of the pavement is much less than the time span over which climate change will have a statistically dependable influence on pavement performance. Only for the pavements with longest life or for the lower layers that may not be touched during future rehabilitation and reconstruction, do road designers need to change their practice at present.' *This is also in line with the information form the ROADAPT users workshop.* 'Accordingly, the few road authorities that have considered climate change appear

[16] Although not explicitly mentioned, this is one of the most important aspects of the threat "Thermal expansion of pavements".
[17] Added in a later stage to Table 1.1 in this report.

to have come to the conclusion that, for the most part, it can be largely ignored as far as the pavement is concerned. Responding to actual weather condition variability by the regular updating of temperature and rainfall levels in design guides will, over the next cycle of the life of the road, automatically provide a response to the small, underlying climate change.' (Dawson & Carrera, 2010).

3.5 SWAMP

The project SWAMP - Storm Water prevention – Methods to predict damage from water stream in and near road pavements in lowland areas focuses on drainage systems at road locations vulnerable to flooding, also known as blue spots (Hellman et al., 2010; Grauert et al., 2010). This project focused on very limited threats, namely damage and hindrance from flooding, although some other threats are mentioned in the questionnaire of Grauert et al. (2010).

These threats were also included in the original version of Table 1.1. in this report.

A questionnaire was sent out and it provided many useful comments on how the different countries in Northern Europe deal with maintenance and repair of drainage systems and whether they use national guidelines. Grauert et al. (2010) mention that results from their questionnaire suggest that most countries have some kind of written guidelines for inspection of national roads and bridges, but they are very different, and treat different aspects of the road drainage system. England, the Netherlands and Ireland have in their current hydrological design calculations already accounted for increased precipitation as a result of future climate changes.

3.6 ERANET ROAD 'Road owners getting to grips with Climate change'

Adesiyun et al. (2011) made a summary report on the ERANET ROAD project IRWIN, P2R2C2, SWAMP and RIMAROCC. *The report does not give additional information on threats or required climate variables*, but it identifies some barriers to the development of the approaches and to their implementation in future:

- Climate modeling: the spatial resolution of global climate models was highlighted as a challenge as was the level of uncertainty in climate modeling, which makes it difficult for decision makers to develop a strategy to deal with climate risks. Probabilistic climate modeling is mentioned as a way to help clarify the uncertainty;
- Uncertainty in future emissions pathways: meaning that it is difficult to recommend a single emission pathway to use for planning purposes;
- Counterproductive policies: some policies may present challenges in addressing the risk of climate change to road networks– for example the EU Water Framework Directive, which limits the amount of water that can be discarded from a site, and may limit actions that can be taken to reduce the risk of flooding at Blue Spot Sites identified;
- Lack of funding/current economic climate: the level of funding for maintenance and inspection of roads has been reduced in many circumstances presenting a potential barrier to the introduction of new approaches which require initial investment. Although it is likely that there will be some initial investment required, it should be highlighted that the approaches, once implemented, will support the prioritization of resources and therefore more efficient and effective use of limited resources available;

- The challenges in developing generic guidelines: The importance of information on local circumstances in assessing the risk of climate change was highlighted which presents a challenge in the development of generic guidelines that are applicable in all European member states.

3.7 EWENT

The project EWENT - Extreme weather impacts on European networks of transport – (Leviäkangas & Saarikivi, 2012) had the objective of assessing extreme weather impacts on the European transport system and monetizing the assessed impacts and to develop draft mitigation and adaptation strategies to make the transport system more resilient against extreme weather phenomena.

The following phenomena were analyzed, based on extensive literature review of more than 150 references (Leviäkangas et al. 2010): strong winds; heavy snowfall; blizzards; heavy precipitation; cold spells; and heat waves. In addition, visibility conditions determined by fog and dust events, small-scale phenomena affecting transport systems such as thunderstorms, lightning, large hail and tornadoes. Events that damage the transport system infrastructure were also considered, but not included in quantitative data analysis.

The report describes the possible impacts of the mentioned extreme events, but no new threats compared to those mentioned in the original version of Table 1.1 were found.

Table 3.3 Most harmful extreme weather phenomena and their threshold values according to EWENT (Leviäkangas & Saarikivi, 2012).

Phenomena	Threshold 1 harmful impacts possible, 0.33	Threshold 2 harmful impacts likely, 0.66	Threshold 3 harmful impacts certain, 0.99
Wind (gust speed)	≥17 m/s	≥25 m/s	≥32 m/s
Snowfall	≥1 cm/d	≥10 cm/d	≥20 cm/d
Rain	≥30 mm/d	≥100 mm/d	≥150 mm/d
Cold (mean temperature of the day)	<0°C	<-7°C	<-20°C
Heat (mean temperature of the day)	≥+25°C	≥+32°C	≥+43°C
Blizzard	Blizzard is considered to occur when Threshold 1 values of Wind, Snowfall and Cold are realised simultaneously		

3.8 WEATHER

The FP7 project WEATHER (Weather Extremes: Impacts on Transport Systems and Hazards for European Regions) aimed at analyzing the economic costs of more frequent and more extreme weather events on transport and on the wider economy and explores the benefits and costs of suitable adaptation and emergency management strategies for reducing them in the context of sustainable policy design (Enei et al., 2011). Table 2 in Enei et al. (2011) gives a list with extreme weather events.

Hail[18] is now mentioned in Table 1.1 in this report, but ash clouds[19] are not.

In general very little information is available on specific thresholds for climate variables, However, WEATHER gives some information on this (Doll & Sieber, 2011). It is not clear whether these thresholds are rough estimates, whether they are based on observations in one or more locations.

The analysis relies mainly on the IPCC A1B and A2 Scenarios with projections of Climate Change to 2050 and 2100 (Enei et al., 2011), thereby indirectly assuming or presenting other emission scenarios as less probable (although the selection may also be due to the availability of information). Information from the ensembles of projections is treated in a probabilistic may (it can be discussed whether this is possible; see also Bessembinder (2015).

3.9 National reports on climate change and roads

In this paragraph a few national reports on the impact of climate change on transport and road infrastructure are discussed.

3.9.1 Dutch report on climate change and transport

Water management and safety in relation to climate change get a lot of attention in the Netherlands, however the reports of the Algemene Rekenkamer (2012) and from PBL (2013) indicated that also other sectors deserve more attention. The report of Maas and Vogel (2014) gives an up-date of the risks and chances related to climate change for the transport sector in the Netherlands. Much of the information used was collected within the research programmes 'Climate changes spatial planning' and 'Knowledge for Climate'. The main risks or threats mentioned in the report are:

- Related to extreme rainfall and storm: damage to roads due to water excess, reduced capacity of roads, displacement of the base of the road;
- Related to extreme high temperatures: deformation of asphalt, reduced functioning of bridges (more difficult to open and close);
- Related to drought: displacement of the base of the road (e.g. instability of peat bodies), traffic hindrance due to road side fires;
- Related to extreme wind gusts: hindrance of large vehicles, blocking of roads due to fallen objects;
- Related to sea level rise and higher river discharges: damage to roads due to water excess, reduced capacity of roads, displacement of the base of the road.

These treats/risks all were included in the original version of the ROADAPT Table 1.1 in this report.

The report also gives some information on required time horizons: for the ICT of road infrastructure a maximum of 5 years ahead is mentioned, but from a perspective of construction the relevant time horizon can be 50 years or more. This last point was also mentioned during the ROADAPT users workshop.

[18] Added in a later stage to Table 1.1 in this report;
[19] Neither are these mentioned explicitly in several of the other WEATHER documents. Ash clouds are not directly related to climate change and therefore outside the scope of ROADAPT.

Maas & Vogel (2014) also mention that the transport sector in the Netherlands is on the verge of major changes, which are already becoming more visible. These changes are motivated by a large spatial pressure, the future shortage of fossil fuels, and the opportunities offered by the rapid developments in ICT.

Figure 3.2 September 10, 2005: Heinenoordtunnel closed due to heavy rainfall (Source: http://www.trouw.nl/tr/nl/4324/Nieuws/article/detail/1549309/2005/09/10/Heinenoordtunnel-dicht-na-regenval.dhtml; http://www.ed.nl/regio/helmond/dunanttunnel-dicht-door-regenbuien-1.2112074)

3.9.2 UK Climate risk assessment

The Climate Change Risk Assessment (CCRA) presents the latest evidence on the risks and opportunities of climate change for the UK to 2100. The findings are presented for a range of possible future scenarios, including different levels of population growth, with an indication of our overall confidence in the results and areas where there are significant evidence gaps. Chapter 7 deals specifically on Buildings and infrastructure. In the overview in this Chapter 7 the following is mentioned related to road infrastructure:

- The national infrastructure has already been identified as priority area for adaptation in ASC (2010). CCRA (2012) shows that flooding is already a major risk;
- The main infrastructure sectors (energy, transport, water and information and communications technology (ICT)) are highly interdependent. Vulnerability in one sector can influence others and failure of critical infrastructure components may lead to ‘cascade failures’ with significant consequences;
- Decisions in the public and private sector on the location and resilience of new infrastructure, on refurbishment of existing buildings, and on how one shapes and maintains the urban environment and public realm will have a substantial impact on future climate vulnerability.

In Par. 7.5 on Transport it is mentioned that ‘extreme weather events can cause severe disruption: snow and ice, flooding, gales, storms at sea and extreme heat all have particular impacts and consequences’ (CCRA, 2012):

- Cold weather, seen in terms of snow and ice, can cause widespread stoppage across whole regions, delaying movement on all modes;
- Flooding incidents, caused by very high rainfall, or by thawing of previous fallen snow, are more likely to damage a section of road or railway at a specific point, sometimes very local. However, it can cause much wider impacts if this breaks a key network link or node:

e.g. a railway or trunk road junction. Also bridge scour may be associated with river flooding or high river flows;

- The UK Coastguard is responding to increasing numbers of incidents at sea, due to busier seas (with increased recreational activities and commercial shipping) and due more frequent and more intense storms that have been experienced in recent years.
- Excessively high temperatures can lead to deformation of road and rail surfaces and to very unpleasant travelling conditions. These incidents can also have serious effects for economic and social activity patterns, through preventing access to services and supply of materials and goods. There is also the potential for an increase in disruption of construction or repair activities at temperatures above 35°C when surfacing of some roads has to be suspended as the asphalt will not cool sufficiently quickly;
- Road subsidence has not been considered as a significant issue by the CCRA.

The above list does not mention threats that were not present in the original version of Table 1.1 in this ROADAPT report.

3.10 Conclusions

The document on 'Adaptation to climate change' from CEDR (2012), gives a good overview of the main effects of climate change for road infrastructure, activities related to adaptation to climate change in a considerable number of European countries and the main projects on this subject. From the documents on international projects and national studies it is hard to determine whether the requirements of NRA's related to climate variables have changed in the past years. In most documents threats are mentioned and regularly also the related climate variables. In the reviewed documents hardly any new threats or climate variables have been identified compared to the original version of Table 1.1 in this report. Those relevant new threats and climate variables mentioned in the former paragraphs are included in the final version of Table 1.1 in this report (in the footnotes it is explained whether they were relevant, and whether they were included).

From inventories on users' requirements (not specifically on road infrastructure) it is known that when people start working on climate change impacts and adaptation, the requests for climate data become more detailed and that e.g. often higher spatial and temporal resolutions are requested.

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Annex 1 ROADAPT user requirements workshop: input from participants

In this annex the input of the participants from the user requirements workshop are presented. The general results are discussed in Chapter 2.

Are relevant climate variables missing?

The following answers were given by the participants (new or other type of variables or information required[20]):

- (No other climate variables required);
- Zero-temperature crossings/thaw;
- Snowfall + (extreme) wind;
- Storm surge (wind in combination with sea level);
- Ground water tables and related pluvial flooding;
- Sunshine duration;
- Ground temperatures;
- Extreme events: storms, floods, heavy precipitation, heat, drought;
- Severe periods: weeks, seasons, cold winters;
- Probability density functions;
- Probability of extreme weather events (drought, rain, snow; 1 day is no problem, but 3 weeks is, and does it happen every year?);
- Uncertainty ensemble approach;
- Probability (of occurrence) of climate scenarios.

[20] The participants at the workshop were from the following countries: Denmark, France, Germany, Netherlands, Norway and Sweden.

Further specification of requirements per time horizon?

Table A1 Results of the Delft workshop (April 2013): further specification of users' requirements by the participants.

	1990-2010	2010-2030	2030-2050	2050-2080	2080-2100
Design/ con-struc-tion	- Current climate information	-Run-off water for design of drainage structures about 50 years -2030-2100: rain intensity -2030: increased risk of aquaplaning	-2030-2100: rain intensity -Road design 10-25 years -Time series for modeling technical features -2050: extreme rainfall 1/25 and 1/100 years for sewage, ditches, etc. -Climate change projections	-2030-2100: rain intensity	-2030-2100: rain intensity -for structures 100 years -2100 design/ construction -to analyze performance road network: hourly rain intensity (2010-2100), exceedance frequencies
Mainte-nance	- Current climate information	-Maintenance 1-5 years -Extreme rainfall intensity for maintenance asphalt 1/10 years -2030: 1hour max. precipitation intensity -2030: statistical predictions for next 20 years	-Time series for modeling technical features -2050: extreme rainfall -Climate change projections		
Opera-tion	- Current climate information - 2010 for planning operational tasks	-2020 -2030: 1hour max. precipitation intensity -2030: statistical predictions for next 20 years			

Which spatial and temporal resolutions needed?

Table A2 Results of the Delft workshop (April 2013): required or used spatial and temporal resolutions[21] by the participants.

	100 m	1 km	10 km	25 km	>50 km
> months		-structure/road design	-structure/road design	-snow operation (de-icing): planning next decade -25-50 km: changes ground water levels/drought	-max. rainfall in month for pluvial flooding -drought + temperatures for forest fires
Weeks		-slope stability	-weeks-months, 1-10 km: when roads frozen enough for passage heavy trucks, when close roads or weight limitation	-maintenance + operation: days with heavy rainfall -maintenance: cycles?	-months-days: for quick scan on impact climate change
Days		-slope stability -landslides -planning maintenance	-10-25 km, weeks-days: pluvial flooding from larger catchments -days-week prediction of storm surges -10-25 km: heat damage to pavements	-snow storm -days-hours: downscale RCM to 'point' data -operation: days with snow cover	
Hours	-Design/construction/performance: precipitation	-maintenance -pluvial flooding of surface drainage -100m-1km design roads/ bridges	-drainage structure dimensioning	-snow operation: nowcasting-3 day advance forecast	-performance of entire road network -road planning, precipitation
Minutes	-Drainage -rain/hail for real-time traffic warning -maintenance/ operation: forecast rainfall	-100m-1km and min.-hours: operation -100m-1km for precipitation warnings -drainage/ runoff systems design		-extreme rainfall for aqua planning	

[21] The spatial and temporal resolutions in this table are based on the experiences with tailoring of climate data of J. Bessembinder. During the workshop in Delft no other categories where proposed by the stakeholders.

Which climate information used for the current and the future?

Table A3 Results of the Delft workshop (April 2013): which climate data used for the current and future climate according to the participants?

	Current	Future
Design/ construc-tion	- rainfall data from KNMI for Rotterdam, period about 1960-2010 - rain intensity curves - very important, but related to measurements of physical impacts - limited to standards (e.g. 1/100 years return for flood) - yes	- rain intensity curves - very important, but related to measurements of physical impacts - 'design' shower for design of infrastructure elements, based on climate scenarios - yes (2 times) - structures with service life of about 100 years need to be designed for future climate. NPRA uses projected climate parameters
Mainte-nance	- based on experience - big need for climate data for right dimension of culverts/drainage - maintenance often includes repair. Data needed relevant for remaining service life (20-30 years?): current data + reserve for future	- should/could be planned for future - yes for planning - big need for climate data for right dimension of culverts/drainage - maintenance often includes repair. Data needed relevant for remaining service life (20-30 years?): current data + reserve for future
Operation	- very important for local + real-time predictions for road users - based on experience - prediction of flooding risks + evaluation of previously determined return patterns of extreme precipitation - not used - data from observational network for frost damage	- not used - year 2030, 2050 + 2100. A1B scenario used to qualitatively predict increased flooding occurrence (where + extend) - for planning and organizing operation activities - current data and security reserve for future - data for future needed to calculate impact of frost damage

Importance of climate extremes for design/construction, maintenance and operation of roads?

Table A4 Results of the Delft workshop (April 2013): importance of climate extremes for the design/construction, maintenance and operation of roads (1=not important, 5 very important).

	Importance climate data				
	1	**2**	**3**	**4**	**5**
Design/ construction	- snow fall	- yes	- pavements (traffic more important factor)	(- rainfall data. No code for importance given, but apparently important)	-yes (5X) - geotechnics and drainage - new roads + structures in roads - geotechnical issues - rainfall extremes for drainage capacity
Maintenance		- yes - extreme rainfall events (drainage capacity)	- yes - shifts gradually, so can be adjusted to current climate -but very important for weather implementation forecasts - but very important for planning maintenance to surface courses (pavement) - design/construction (10-25 years)	- maintenance planning	- snow fall - but probably currently not used very much
Operation	-But very important for weather forecasts	- (more based on weather statistics and experience)		- yes	- for real-time local weather forecasts

Sources of climate data and information?

Table A5 Results of the Delft workshop (April 2013): where do NRA and others working on the impacts of climate (change) on roads get their climate data.

	Sources of climate data
Design/ construction	- KNMI - SMHI - DWD - current data and statistics: eklima.met.no; future projections: from leading national report 'Climate in Norway 2100' - SMHI (2X); from the network of weather stations of the Swedish transportation Administration (not widely used); climate change data regionally and nationally: SMHI - KNMI (rainfall data) - Meteo France (and some private providers) - KNMI, IPCC, Delta programme - current climate: KNMI (including E-OBS), CRU, GMS database (RWS); future climate: ENSEMBLES, KNMI
Maintenance	- DWD - SMHI (3x) - eklima.met.no (database with possibility to order reports/statistics) - KNMI
Operation	- DWD - DMI and IPCC - web portals and databases, measurements + statistics: eklima.met.no current/historical/forecasts: www.senorge.no - SMHI

The use of national or international standards?

Table A6 Results of the Delft workshop (April 2013): presence and use of national or international standards?

	National standards	International standards	Experience	Other …
Design/ construc-Tion	- yes in Netherlands - national standards for France and EUROCODES? - RijksWaterStaat regulations - statistics of KNMI for extreme precipitation; 'worst case scenarios with 1/10 years frequency' - hydrographs for drainage design (in Netherlands	- national standards for France and EUROCODES?	- some in-house experience for hydraulic network dimensioning - a lot of design guidelines are typically based on experiences. Need to be made explicit - usually form pilot cases from large European projects - learned in past years about aqua planning that risks and flooding risks of e.g. tunnels is that both thresholds and background of used data are 'unknown'/based on experience	- national or project specific
Mainte-nance	- standards (France?) - the formula for drainage capacity contains 'precipitation intensity' for a chosen return period and frequency; lack of data for 2050 and 2100 there current situation multiplied with 'climate factor' - statistics of KNMI for extreme precipitation; 'worst case scenarios with 1/10 years frequency'		- yes in Netherlands - experience from companies/contractors very relevant (Sweden). How to get and maintain this knowledge is the challenge - no database for landslides/natural hazards (Sweden). How to collect experience?	- lack of data for 2050 and 2100, therefore current situation multiplied with 'climate factor' (guestimate)
Operation	- national standards and statistics (Denmark) - some national standards + guidelines (France)		- yes in Netherlands - based on previous events of flooding (Denmark), both geographically and to levels of extend - experience from companies/contractors very relevant (Sweden). How to get and maintain this knowledge it the challenge - EASYWAY guidelines for CERAT	- EASYWAY guidelines for CERAT

Dealing with uncertainties in climate data?

Table A7 Results of the Delft workshop (April 2013): ways of dealing with uncertainties for the design/construction, maintenance and operation of roads.

	Dealing with uncertainties			
	Upper/lower limits	**Statistics**	**1 or more scenarios**	**Other …**
Design/ construc-tion	- for the 'blue spots project' in the Netherlands the worst-case-scenario was used, and nothing else with uncertainties (one could argue whether this approach was good) - usually we take account of conservative(exaggerated) values - for large and important structures Met.no and inst. For water resources are requested to give specific advice - change of climate (extreme levels) for a certain place and over a time interval - mostly used today (flood 1/100 years, rainfall, temperature)	- from SMHI data, statistics (2X), probabilities, ready for use - mostly used today (flood 1/100 years, rainfall, temperature) - probabilistic modeling of rain intensity, using copulas (not only using upper/lower limits) - most design guidelines based on statistics, may include extreme values	- idem 'blue spots project' - KNMI scenarios - for regional flooding analysis - several scenarios whenever possible - different climate models from ENSEMBLES, mostly with same emission scenario - ensemble approach - spatial differences of climate change: mean value of different models - SMHI uses various scenarios (2X)	
Mainte-nance	- experience - idem 'blue spots project' - change of climate (extreme levels) for a certain place and over a time interval	- experience - guidelines for drainage capacity and erosion protection include 'climate factor' >1 for extra security. In addition advice given to use the newest data		
Operation	- experience - basically we follow the directions given in the IPCC report, but uncertainties increase with longer time horizons. Underlining a upper and lower limit to an analysis, based on the given margin of confidence	- experience - uncertainties have to be dealt with when formulating contracts: e.g. what to consider as 'normal' situations	- basically we follow the directions given in the IPCC report, but uncertainties increase with longer time horizons. Underlining a upper and lower limit to an analysis, based on the given margin of confidence	