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ROADAPT
Roads for today, adapted for tomorrow

Guideline part E:
Selection of adaptation measures and strategies for mitigation

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Executive summary

The output of the ROADAPT project consists of five guidelines for evaluating the effect of Climate Change on the road network and take remedial action concerning design, construction and maintenance of the road network:
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

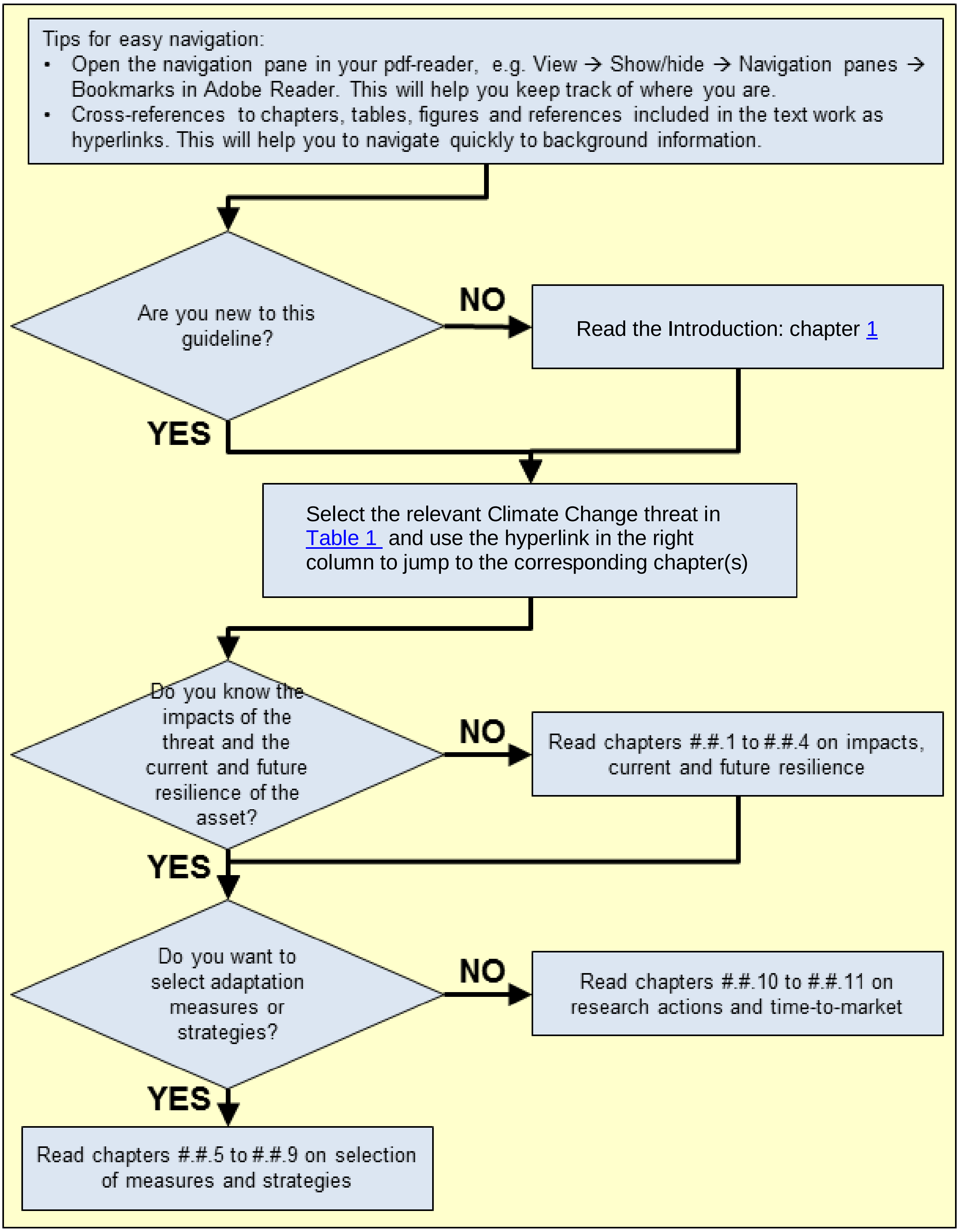
The underlying part E of the ROADAPT guidelines presents an overview of adaptation measures and helps in selecting an adaptation strategy. This guideline is meant to be used in conjunction with the ROADAPT database of adaptation measures.

The selection of the adaptation strategies follows a 10 step approach that can be applied to various climate change threats. The first 3 steps of the 10 step approach guide the user through the process of understanding the impacts of climate change, current and future resilience of the assets. The next 5 steps help the user select adaptation measures and adaptation strategies. The two final steps provide an outlook on research that will help climate change adaptation, also estimating the time-to-market to support compilation of research road maps.

The 10 step approach is applied to the main threats of flooding of the road surface (assuming no traffic is possible), erosion of road embankments and foundations, landslips and avalanches, loss of road structure integrity, loss of pavement integrity, loss of driving ability due to extreme weather events and reduced ability for maintenance.

Quick-start guide

This part of the ROADAPT guideline is quite extensive. The following quick start guide helps you find your way.



1 Introduction

1.1 The ROADAPT project

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 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 quickscan 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 mobility services.

The output of the ROADAPT project consists of 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

The underlying guideline is part E, dealing with the selection of an adaptation strategy.

1.2 How to use this guideline

This part of the guideline presents an overview of adaptation measures and helps in selecting an adaptation strategy. This part of the guideline provides practical support in RIMAROCC step 5: Risk Mitigation. This assumes that the previous RIMAROCC steps have been performed or that the QuickScan approach and the ROADAPT Vulnerability Assessment have been conducted (parts B and C of the guidelines), and that relevant climate change threats, assets types under threat and vulnerable locations are known. Table 1 lists the climate change threats and assets that this guideline deals with.

Table 1: Overview of climate change threats dealt with in the chapters of this guideline

Main threat	Specific threat	Asset under threat	Chapter
Flooding of road surface (assuming no traffic is possible)	Flooding due to failure of flood defence system of rivers and canals	Pavements, road embankments	2.1 Hydraulic capacity of culverts 3.1 Stability of road embankments after flooding from external sources
	Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)	Pavements, road embankments	2.1 Hydraulic capacity of culverts 2.2 Hydraulic capacity of road drainage systems 3.1 Stability of road embankments after flooding from external sources
	Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges	Pavements, road embankments	2.1 Hydraulic capacity of culverts 3.1 Stability of road embankments after flooding from external sources
	Flooding from snow melt (overland flow after snow melt)	Pavements, road embankments	3.1 Stability of road embankments after flooding from external sources
Erosion of road embankments and foundations	Overloading of hydraulic systems crossing the road	Culverts, road embankments	2.1 Hydraulic capacity of culverts 3.4 Erosion of road embankments and foundations
	Erosion of road embankments	Road embankments	3.4 Erosion of road embankments and foundations
	Bridge scour	Bridges	3.4 Erosion of road embankments and foundations
Landslips and avalanches	External slides affecting the road	Road	3.2 Slides of the embankment after heavy rain / heavy rain after dry period / landslides
	Slides of the road embankment	Road embankments	3.2 Slides of the embankment after heavy rain / heavy rain after dry period / landslides
	Debris flow	Road	3.2 Slides of the embankment after heavy rain / heavy rain after dry period / landslides
	Rock fall	Road	3.2 Slides of the embankment after heavy rain / heavy rain after dry period / landslides
	Snow avalanches	Road	3.2 Slides of the embankment after heavy rain / heavy rain after dry period / landslides
Loss of road structure integrity	Increasing soil moisture levels, affecting the structural integrity of roads, bridges and tunnels	Pavements, road embankments	3.1 Stability of road embankments after flooding from external sources
	Weakening of the road base and road embankment by standing water	Pavements, road embankments	3.1 Stability of road embankments after flooding from external sources
	(Unequal) settlements of roads by consolidation	-	-

Main threat	Specific threat	Asset under threat	Chapter
	Instability / subsidence of roads by thawing of permafrost	-	-
	Uplift of tunnels or light weight construction materials by increasing groundwater levels	Tunnels, road embankments	3.3 Uplift of tunnels or light weight construction materials by increasing water levels
Loss of pavement integrity	Cracking, rutting, embrittlement	Pavements	4.1 Heat stress on bituminous and semi-rigid pavements 4.2 Heat stress on concrete pavements
	Frost heave	-	-
	Aggregate loss and detachment of pavement layers due to frost	-	-
	Aggregate loss and detachment of pavement layers due to sustained wetting	Pavements	3.1 Stability of road embankments after flooding from external sources
	Cracking due to weakening of the road base by thaw	Pavements	4.3 Pavement deterioration by spring thaw
	Thermal expansion of pavements	Pavements	4.2 Heat stress on concrete pavements
	Decreased utility of (unimproved) roads that rely on frozen ground	Road	4.3 Pavement deterioration by spring thaw
Loss of driving ability due to extreme weather events	Reduced visibility	Road	5.2 Mobility Services during extreme weather
	Reduced visibility during snowfall, heavy rain including splash and spray	Drainage systems	2.2 Hydraulic capacity of road drainage systems
	Reduced vehicle control due to heavy winds	Road	5.2 Mobility Services during extreme weather
	Decrease in skid resistance on pavements from slight rain after a dry period	Road	5.2 Mobility Services during extreme weather
	Aquaplaning in ruts due to precipitation on the road, splash and spray	Pavements Drainage systems	2.2 Hydraulic capacity of road drainage systems 4.1 Heat stress on bituminous and semi-rigid pavements
	Decrease in skid resistance on pavements from migration of liquid bitumen	Pavements	4.1 Heat stress on bituminous and semi-rigid pavements 4.2 Heat stress on concrete pavements
	Icing and snow	Road	5.2 Mobility Services during extreme weather
Reduced ability for maintenance	Snow removal costs	-	-
	Ice removal costs	-	-
	Impact on road works: decreased time window for paving	Pavements	4.1 Heat stress on bituminous and semi-rigid pavements 4.2 Heat stress on concrete pavements

Main threat	Specific threat	Asset under threat	Chapter
Susceptibility to wildfires that threaten the transportation infrastructure directly		-	-
Damage to signs, lighting fixtures and supports		-	-
Trees falling on the road		-	-

Chapter 1.3 presents the 10 step approach towards selecting an adaptation strategy. Chapter 1.4 gives an overview of general adaptation measures. Chapter 1.5 introduces the ROADAPT database of adaptation measures for specific climate change threats.

The chapters 2 to 5 show the application of the 10 step approach to the specific threats given in Table 1.

The adaptation measures collected in this guideline have been derived from an extensive literature survey, covering all climate zones of Europe. Adaptation measures will apply to most European countries. However, network and traffic characteristics, practices and materials and priorities of the road owner vary from country to country. For that reason, the user of this guideline should verify that applications of measures comply with these factors.

1.3 The 10 step approach for selecting an adaptation strategy

The ROADAPT approach towards selecting an adaptation strategy is based on the following needs with respect to formulating an adaptation strategy:

- To develop a structure for decision making, corresponding to the need of the road owner. This structure should be consistent and applicable on the level of a road network, a road section and a structure.
- To present an overview of decisions that should be taken in the adaptation process, and factors influencing the choices the NRA makes.
- To find out which techniques to apply, when and why.

A 10 step approach has been developed to answer to these needs. For every climate change threat the 10 steps listed below allow the road owner to select an adaptation strategy for the vulnerable road component (asset) under consideration. Chapters 2 to 5 describe the application of the 10 steps to the specific threats listed in Table 1.

Steps 0 to 3 provide background information on the road owner's needs, impacts and current and future resilience. Steps 4 to 8 deal with the selection of adaptation measures and strategies. The selection process involves:

- Selection of a combination of measures that constitute an adaptation strategy.
- Ranking of measures according to the assessment of their consequences for operation and sustainability.

Steps 9 and 10 provide an outlook on research that will help climate change adaptation, also estimating the time-to-market to support compilation of research road maps.

Step 0: What are the road owner's needs?
This step identifies the relevance of the specific threat for the road owner, the specific needs of the road owner other than the general needs given before, and the damage mechanisms activated or strengthened by climate change.

Step 1: Definition of the relevant climate variable from design guidelines
This step gives:
a) The way that current design guidelines for the asset deal with the specific threat.
b) The climate variable that is used in design guidelines related to the threat (this includes time series, spatial and temporal resolution, and thresholds).
c) The rate of change of the climate change impacts.

Step 2: Resilience of the asset in current situation
This step is to be performed by the road owner, since it is site and construction specific. The step provides practical guidance for the case-by-case analysis:
a) How to estimate the current resilience of the asset.
b) What other factors may affect resilience, such as ageing of materials and traffic loading.
c) The availability of hidden safety margins that are not explicitly addressed in the design, but that can be used to buffer the impact of climate change.

Step 3: Resilience of the asset in possible future situations
This step gives:
a) An estimate of the amount of climate change for the climate variable.
b) An estimate of the impact of climate change on the resilience of the asset.

Step 4: Identification of applicable / appropriate adaptation measures
This step gives the list of adaptation measures from the ROADAPT database.

Step 5: Establishing a policy
This step presents the policy matrix for the specific threat, also showing the individual adaptation measures in the matrix in Figure 1.

In the matrix of Categories of measures vs. Stages of an extreme event, policies can be seen as logical combinations of measure categories and stages. Policies are the building blocks for adaptation strategies to be developed in Step 7.

The colours of the policies in the matrix indicate the adaptation strategy to which they contribute:
- ‘Do minimum’ and ‘Develop contingency plans’ strategy
- ‘Future-proof designs’, ‘Retrofit solutions’ and ‘Update operating procedures’ strategies
- ‘Monitoring’ strategy
- ‘Research’ strategy

A similar policy matrix has been used successfully to visualize the Dutch approach to flood protection. The matrix shows that different policies can coexist. The current overall flood protection strategy in the Netherlands is the ‘multiple-layer safety’ strategy: a combination of policies is considered more cost-effective than the traditional approach that focusses on prevention only.

Figure 1: Policy matrix

<table>
<tr><th colspan="2" rowspan="2"></th><th rowspan="2">PRO-ACTION</th><th rowspan="2">PREVENTION</th><th colspan="2">PREPARATION</th><th colspan="2">RESPONSE</th><th>RECOVERY</th></tr>
<tr><th>In preparation of an extreme event</th><th>Just before an extreme event</th><th>During an extreme event</th><th>Just after an extreme event</th><th>After an extreme event</th></tr>
<tr><td rowspan="9">CATEGORY OF ADAPTATION MEASURE</td><td>Planning for Climate Change Impacts and Extreme Weather Events</td><td rowspan="3">Pro-active attitude</td><td></td><td></td><td colspan="4" rowspan="2">Extreme event management</td><td></td></tr>
<tr><td>Robust construction</td><td colspan="2" rowspan="2">Prevention</td><td></td></tr>
<tr><td>Legislation , regulations</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Resilient construction</td><td></td><td colspan="2">Upgrade, Retrofit and New Construction</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Maintenance and management</td><td></td><td></td><td>Preventive Management and Replacement</td><td></td><td></td><td></td><td>Corrective Management and Replacement</td></tr>
<tr><td>Traffic management for Climate Change Impacts and Extreme Weather Events</td><td></td><td colspan="6">Traffic Management</td></tr>
<tr><td>Capacity building</td><td colspan="7">Capacity Building</td></tr>
<tr><td>Monitoring</td><td colspan="7">Monitoring and Prediction</td></tr>
<tr><td>Research</td><td colspan="7">Research</td></tr>
</table>

‘Do minimum’ and ‘Develop contingency plans’ strategy
‘Future-proof designs’, ‘Retrofit solutions’ and ‘Update operating procedures’ strategies
‘Monitoring’ strategy
‘Research’ strategy

The definition of the stages along the horizontal axis of the policy matrix is:

- PRO-ACTION: activities in this stage aim to rule out the possibility of an extreme event, e.g. flood defences to prevent flooding. The objective of this stage is to enable smooth and safe traffic.
- PREVENTION: activities in this stage aim to eliminate vulnerability, e.g. raising a road above the High Water Level. The objective of this stage is to enable smooth and safe traffic.
- PREPARATION – In preparation of an extreme event: aActivities in this stage aim to reduce consequences, e.g. erosion proofing of a road. The objective of this stage is to support disaster consequence reduction.
- PREPARATION – Just before an extreme event: activities in this stage aim to support evacuation, e.g. provide shelter locations. The objective of this stage is to provide an evacuation and life supply route.
- RESPONSE – During an extreme event: activities in this stage aim to minimize damage, e.g. shutting down systems. The objective of this stage is to minimize the loss of functions.
- RESPONSE – Just after an extreme event: activities in this stage aim to guide emergency transport, e.g. restricting heavy traffic on saturated roads. The objective of this stage is to provide access for repairs and humanitarian aid.
- RECOVERY – after an extreme event: activities in this stage aim to restore transport functionality, e.g. deployment of repairs. The objective of this stage is to provide access for recovery of affected area.

The definition of the measure catagories along the vertical axis of the policy matrix is:

- Planning for Climate Change Impacts and Extreme Weather Events: developing plans to respond to evolving climate change risks so that their immediate effects can be managed.
- Robust construction: developing alternative construction methods aimed at eliminating vulnerability.
- Legislation, regulations: updating legislation and design and operational requirements, including technical standards and specifications, to provide additional capacity / functionality.
- Resilient construction: developing alternative construction methods aimed at reducing impacts.
- Maintenance and management: keeping the assets in proper condition, or preparing the assets for climate change or extreme weather events.
- Traffic management for Climate Change Impacts and Extreme Weather Events: managing traffic flows to keep the transport system available, uncongested, safe or environmentally sustainable during extreme weather events.
- Capacity building: increasing the capacity of road owners and/or the public to deal with the impacts of climate change.
- Monitoring: monitoring of the rate of climate change and/or its impacts to increase confidence in the appropriate adaptation option, or to predict the time of implementation.
- Research: obtaining a better under-standing of likelihood and consequences of risks of climate change, or determining or refining appropriate adaptation options.

Step 6: Assessment of consequence criteria for measures

This step identifies the consequences of the applying the adaptation measures by a semi-quantitative rating of the criteria Availability of the road, Safety of road users, implications for Network operation, Direct cost for the road owner and Reputation of the road owner. The assessment is also given in the ROADAPT database. The rating may be used to prioritize between measures. The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts. E.g. the impact of flooding on availability is more serious than a reduction of driving ability in a heavy rainstorm.

Step 7: Decision on the most appropriate strategy and shift from one strategy to another
This step is to be performed by road owner. This guideline provides the applicable strategies, their consequences and the criteria for selecting or changing strategies.

Step 8: Stakeholders to be involved
This step lists stakeholders that are required for implementation of the strategies.

Step 9: Existing knowledge gaps
This step gives an overview of knowledge gaps in climate parameters, upcoming techniques / measures and data that are needed to assess the resilience of the asset. The upcoming techniques / measures have been extracted from the database and from literature sources.

Step 10: Time to market of upcoming techniques
This step estimates the time that is required to bring the upcoming techniques / measures from Step 9 to the market. Also, the Technology Readiness Level of the measures is given.

1.4 Adaptation measures – general

A task group of CEDR has suggested general actions that NRA can undertake to deal with climate change. The CEDR report ‘Adaptation to climate change’ [2] gives general measures that can be incorporated in an adaptation strategy for climate change. The report also gives examples of best practices.

Table 2 presents an overview of general measures inspired by the CEDR report, and the corresponding steps in the RIMAROCC [12] and ROADAPT approaches for implementation of these measures.

Table 2: Overview of general measures in relation to RIMAROCC and ROADAPT approaches

Measure	RIMAROCC approach	ROADAPT approach
Develop a strategy for climate change adaptation as a continuous, cyclic process; embed this strategy in the NRA primary processes	Step 1: Context analysis	-
Create awareness among funding agencies about the impacts of climate change mitigation – present high level indicators for availability, road user safety, network operation, cost for the NRA and society, and reputation of the NRA	Step 1: Context analysis	-
Make an inventory of current climate change projections at the appropriate temporal and spatial scales	Step 2: Risk identification	Guideline part A: climate change projections
Make an inventory of site and construction specific data needed for risk analysis, evaluation and mitigation	-	Guideline part B: quick scan Guideline part E: adaptation strategy
Plan for carrying out a survey of vulnerable assets – assessing the risk arising from climate change.	Step 2: Risk identification	Guideline part B: quick scan
Analyse and evaluate risks of climate change impacts on vulnerable assets.	Step 3: Risk analysis Step 4: Risk evaluation	Guideline part C: detailed vulnerability assessment
Make an inventory of (socio-)economic aspects: estimating the costs and benefits of actions (compared to the costs of no action) and relating the investments to risk level.	Step 4: Risk evaluation	Guideline part D: socio-economic impact assessment Guideline part E: adaptation strategy
Select strategies for action and adaptation measures.	Step 5: Risk mitigation	Guideline part E: adaptation strategy
Prepare a strategy for implementation: formulating action plans, encouraging political effort / legislation.	Step 6: Implementation of action plans	
Implement adaptation measures on the technical side: adjusting guidelines for planning and design, other technical procedures, adjusting methods for risk assessment.	Step 6: Implementation of action plans	Guideline part E: adaptation strategy
Implement strategies for improving the knowledge basis: promoting research, adapting results from climate research for practical use, etc.	Step 6: Implementation of action plans	-
Implement strategies for improving communication to road users, both before and after weather related events.	Step 6: Implementation of action plans	-
Implement a plan for monitoring of climate change, climate change impacts and effects of adaptation measures	Step 7: monitoring, review and capitalisation	Guideline part E: adaptation strategy

Measure	RIMAROCC approach	ROADAPT approach
Ensure a clear and well-communicated role for the NRA in securing a functional transport system.	-	-
Develop improved specifications for risk-based functionality and criteria for defining acceptable risk level	-	-
Coordinate research and education activities: • dissemination, knowledge transfer and implementation of research results; • coordination of research programmes, trans-European joint programming; • better collaboration between on-going research projects; • raising awareness among the general public and politicians; and • ensuring that academic education includes adaptation issues.	-	-

1.5 Adaptation measures – the ROADAPT database

The ROADAPT database of adaptation measures is provided as an excel spreadsheet and contains over 500 measures. The current version is 9.2.

The excel filter options allows an easy selection of the measures as a basis for action plans. The following criteria are available for selection:

- Main threat, as listed in Table 1.
- Specific threat, as listed in Table 1.
- Climate parameter causing the threat.
- Asset type for which there is an impact.
- Policy, meaning the approach adopted to mitigate the threat, as in Figure 1.
- Category of measure, meaning the type of activity, as in Figure 1.
- Stage, meaning the moment with respect to the occurrence of an extreme event, as in Figure 1.
- Scale for which the measure should be deployed, from a single object to national network.

Also, the database gives a semi-quantitative rating of the performance of the measure with respect to the criteria Availability of the road, Safety of road users, implications for Network operation, Direct cost for the NRA and Reputation of the NRA. The criteria and the rating are derived from the risk evaluation study for the Netherlands highway network [32], and are explained in Annex A.

The contribution to sustainability is characterized by an overall classification ('green' or 'not green'), and by a rating of the performance of the measure with respect to the criteria General / Management, Climate change and Energy, People and Communities, Ecology / Biodiversity, Physical resources, Quality of Life and Safety, Health & Equity. The criteria are based on the criteria commonly found in sustainability assessment schemes. The criteria and their rating are explained in Annex B.

2 Culverts and Drainage

2.1 *Hydraulic capacity of culverts*

This chapter deals with malfunctioning of culverts across the road. This impact is also referred as “deterioration of drainage capacity of culverts”.

In this part, concerned facilities are small and medium hydraulic structures (circular or rectangular) which convey natural run-off water across (or parallel to) the road. Bridges are considered in other parts of the report.

2.1.1 *Step 0: The road owner’s needs*

Climate change
The CEDR report on Climate change [2] summarizes the expected climate changes during the twenty-first century:

- Regarding **rainfall**, contrary tendencies are expected between north and south concerning mean precipitation whereas a general increase in extreme intensity is indicated: “While annual precipitation is likely to increase in the north and decrease in the south, the intensity of daily precipitation and the probability of extreme precipitation intensities may increase in all regions”.
  It is important to add that predictions for mean annual amounts of rainfall are far better known than for extreme events. **These extreme rain events are the most difficult parameter to assess with the predictions models.**
- Model predictions indicate that the **mean annual temperature** will rise by between 1 and 5.5°C.
- The **sea level** in some areas is likely to rise by up to 0.9 m by the end of the century,
- **Mean annual wind** speeds are expected to increase in the northern regions, while possibly decreasing in the Mediterranean regions. **Extreme wind speeds** may increase in western and central Europe and in the North Sea area.

Impacts of climate change
Extreme rainfall intensity events will increase as a result of climate change, resulting in malfunctioning of culverts crossing the road:

- Overloading of the culvert causing higher backwater, erosion and flooding (on the road and / or in the adjacent lands,
- Obstruction of the culvert by floating debris causing flooding. This damage may by aggravated by **wind** and **hail**.

Temperatures will increase resulting in drier soils and decrease of vegetation cover causing more run-offs on lands. This run-off will increase the peak flow towards culverts which will be overloaded (see before).

The **sea level** rise will decrease the evacuation capability of culverts (downstream control) causing higher upstream water depths.

Effects of damage
The damage from higher rainfall events, temperatures and sea level rise will cause:

- A decrease in availability due to maintenance -replacement -rehabilitation works or traffic interruption.

- A reduction in driver safety because of unexpected water on the pavement and sometimes traffic interruption.
- An increase in maintenance -replacement -rehabilitation cost.
- A loss of confidence of the public in the ability of the road owner to deal with climate change impacts.

Concerns of the NRAs

The PEB members identified the following specific road owner's problems related to culverts:

- It is necessary to ensure sufficient drainage capacity for the remaining service life of the structure, which is XX years (to be decided by the road owner) → see chapter 4.1.8
- The design rules require a capacity corresponding to the YY-year runoff. → see chapter 4.1.8
- Data on precipitation and other factors influencing runoff are available, but their quality might not be adequate. → see chapters 2.1.2 and 4.1.8
- What kinds of climate data are needed? → see chapters 2.1.2 and 4.1.8
- What is the best way to adapt? Which adaptation technique should be applied and when? → see chapter 4.1.8

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs. Regarding culverts capacity, in annex 1, we will focus on the increase of rainfall intensities, flow rates in rivers, flood and sea level rise.

The risk is considered serious by NRAs as follow, in decreasing order:

- Flood : Ten out of eleven NRAs,
- Higher rainfall intensity : Nine out of eleven NRAs,
- Increased flow rates in rivers :Five out of eleven NRAs,
- Sea level rise: Four out of eleven NRAs.

The main concerns and needs are the following:

- Norway, Finland and France mention problems related to insufficient erosion protection, damage to culverts, blocking of road, flash floods, and damage to gravel road structures ,
- Several strategies or actions are already implemented in 9 countries (Norway, Finland, Sweden, Denmark, United Kingdom, Ireland, France, Austria and Spain) :
    - Guidelines : Improved guidelines for erosion construction and inspection, review of guidelines for design, increase of rainfall intensities for calculations, national adaptation plan,
    - Studies and mapping : risk and susceptibility analyses, mapping of risk areas, improved spatial planning,
    - Extreme event management : improved emergency plans, adapted traffic,
    - Maintenance: inspection routines
- Eight countries indicate the needs for research on:
    - Better forecast on precipitations (spatial and temporal), flood level and sea level rise (Norway, Sweden, Denmark, France, Spain),
    - Design standard review (Finland),
    - Impacts, protections (efficiency of natural and artificial protection) and costs (Ireland, France, Italy)

2.1.2 Step 1: Definition of the relevant climate variable from design guidelines

Vulnerable asset
Increase of rainfall intensities is the most important cause of overloading of culverts crossing the road. Especially in rural areas also longer wet periods in combination with intense rainfall might be critical. Temperature and seal level rise are aggravating factors (see before) especially regarding obstruction by floating debris. According to the increase range, this overloading can involve different impacts from higher backwater without damage to serious impact on adjacent lands and driver's safety and therefore a loss of reputation for NRA.

This impact is greater especially in vulnerable areas (urban or industrial areas, sensitive agricultural and natural lands…).

Useful climate variables
The climate variables used for capacity design are the **intensity-duration-frequency curves** (IDF curves) presenting for different return period (frequency in year) the evolution of the rainfall intensity (mm/hr) according to the duration of the rain event (min).
The duration is usually comprised between a few minutes to one or 2 days. These curves are currently based on statistical analysis of historical and present records values.

The return period (frequency) needs to be decided by the road owner according to the acceptable risk (for the road itself and the adjacent area) and the needed level of services.

For a chosen return period, the **maximum rainfall intensity** (in mm/h) from IDF curves is used to define the expected peak discharge (in m^3/s) for each culvert.
For some studies**, storm profiles** can also be used. It consists of a typical storm distribution (chosen shape) which is implemented on watersheds to represent the evolution of the rainfall intensity according to the time. The rainfall characteristics are based on IDF curves.

Relationship between consequences and threats
In general, the higher the rainfall intensities are, the higher the flood may be (by depth and /or area and / or duration). Nevertheless, this relationship has to be nuanced according to the following thresholds by increasing order:

- **Normal operation**: the upstream backwater is consistent with the needed level of service (for example in France, water depth below 1.2 times the culvert height),
- **Critical operation**: the water depth reaches the value that involves a degradation of the culvert conveyance (For example in France, limit of free surface flow),
- **Breach level**: the flood reaches the road and involves an interruption of traffic.

We may also add a fourth level regarding the environmental background. This level is not directly linked to the road but indicates the water depth value from which houses, industrial sites or other roads are flooded.

The threshold values (extreme rainfall intensities values) depend on the type, size and gradient of the culverts as well as the watershed features.

Present knowledge regarding climate parameters
As summarized in the RIMAROCC guidebook, the present knowledge regarding **maximum rainfall intensity** indicates a moderate increase since the 1961-1990 period. Regarding frequency, a moderate increase has also occurred in north Europe. The qualitative foresights assess the certainty of predictions as likely e.g. above 66 % probability of occurrence. The time horizon is still quite difficult to define nevertheless some statistical evidence of trends are already observed (more extreme events since the 80s in France).

Regarding **sea level rise**, a significant increase (above 0.2 m) is virtually certain in 2100. For **temperature**, a significant global increase (1.8 to 4°C) is virtually certain in Europe. **Extreme wind speed** is also likely to increase in a moderate way.

2.1.3 Step 2: Resilience of the asset in current situation

Assess the current capability of the culvert

In order to know the current resilience of the culvert at a particular point, the road owner shall follow the steps below:

- Collect the needed site data :
    - ***Structural data*** based on measurements, topographical survey, documentation and site visit:
        - Facility features: date of construction, shape, dimensions, longitudinal gradient, material, upstream and downstream inlet features and erosion protections,
        - Watershed features: total surface area drained into the culvert, mean slope, type of actual cover
    - ***Rainfall data*** (IDF curves) for estimating peak flow to discharge using the relevant national methodology (or without prescriptions the worldwide known rational method).

      The value of the peak flow will depend on the chosen return period and the situation we want to simulate: actual value issued of the stage design, actual value issued of the stage design with a safety margin, expected value based on predictions or chosen risk analysis
    - ***Adjacent assets at stake***: vulnerable areas in the vicinity of the site (urban or industrial area, others transport infrastructures…)
- Calculate the stage-discharge curves of the culvert by the use of a software calculating the water profile within the facility. These curves define the functioning of the culvert in several cases:
    - The culvert conveys the flow for the optimum conditions (no obstruction within or downstream): **optimum operation**.
    - The culvert conveys the flow for the actual conditions of the facility as visualised during site survey: **normal operation**.
    - The culvert conveys the flow for the actual conditions of the facility as visualised during site survey: normal operating,An aggravating factor involves floating debris and obstruction: **aggravated operation**.

  If necessary, an analysis of the potential upstream storage (floodable area) or diverted flows (in auxiliary culverts or low points) is done.
- Carry out the diagnosis of the culvert by comparing the stage-discharge curves to the various peak discharges. This diagnosis may show from which peak flow value (linked to the climate change) the road is submerged.

  At that stage, it is also important to study the consequences of upstream water level rise on the upstream area: increase of flooded surfaces, human assets affected (urban areas, agricultural areas, other infrastructures…)

Extra-capacity

Nowadays, **safety margins** are already taken into account because a large part of the culverts are designed considering a **maximum filling ratio** for the design calculations (around 75% in France, **minimum freeboard** of 300 mm to 600 mm in the UK).

For **high fill road**, the water depth may increase significantly before reaching the traffic lanes creating artificial safety margin. Nevertheless, the impact of backwater has to be defined within the upstream area (flooding of housing, industrial areas or lower infrastructures).

Moreover, the culvert design is often checked for a rainfall event above the chosen design event (extreme peak flow in France equal to 1.5 to 1.8 times the design peak flow).

For all Europe, we can also consider than a **spare capacity** can be gain with a rigorous maintenance routine especially in vulnerable areas: urban areas, sag points…

2.1.4 Step 3: Resilience of the asset in possible future situations

In this step, we will focus on the rainfall intensity variable. Actually, other climate variables (temperature, sea level rise and wind) have impacts on culvert but may be considered only as aggravating factors.

Predictions for rainfall intensities
Rainfall data on climate change are usually treated on a day basis whereas the critical events for culverts have shorter durations. Actually, the critical duration is based on the time of concentration which usually ranges from 15 min to some hours.

It is also difficult to represent extreme rainfalls with most of the predictive models especially because of their scales (even with regional models with 25 or 50 km spatial resolution) which are not consistent with the intense rainfall generation.
Moreover, uncertainties of model for extreme rainfall are significant. Some French scenarios predict an increase of intensities although others predict a decrease.

It shows that it is difficult to use the predictions of climate change for rainfall parameters, even if some studies show that the ratios between short duration rainfalls and daily rainfalls are quite constant.

Thus some studies advise to work on emergency plans (above the design event) and aggravating factors of flooding (urban planning, land uses in floodplains, extreme events risk management).

Climate change and culvert capacities
An increase of the rainfall intensity will immediately result in a rise of the peak flow discharge resulting in an increase of water depth in the culvert.

The damages will depend on the chosen criteria at design stage especially freeboard and the longitudinal profile of the road.

Regarding water depth, three levels are possible, the water profile:

- remains in the culvert due to freeboard (**safety margin**) → no hazard for drivers
- exceeds the culvert height but do not reach the traffic lanes (**extra capacity** due to fill) → no hazard for drivers
- reaches the traffic lanes and submerges the road → high hazard for drivers

Of course for important flood involving high velocities and / or debris, the risk is higher due to erosion that may ruin the culvert.

As indicated before, the upstream area must also be included into this study in order to define thresholds regarding adjacent residents and assets. Additional or sub-thresholds may be added according to the upstream land use.

Data to define resilience in the future
As seen before and on the contrary to other values (temperature for example), it is still highly difficult to predict the value of the rainfall intensity increase.

In order to be sure of when the culvert capacity will be exceeded (internal capacity + safety margin + extra-capacity), a precise amount of extreme values are needed.

This may be possible by the following ways:

- decreasing the model spatial scale to be closer to the generative rainfall cell size,
- sharpening the different scenarios,
- mapping precisely flood areas,

2.1.5 Step 4: Identification of applicable / appropriate adaptation measures

Methodology
External and internal threats are considered separately. For each, measures outside the road owner's easement are indicated (measure underlined in the tables). Measures that are linked to the same subject are listed together.

Internal threats considered are pluvial flooding, overloading of culverts and erosion of road bases due to extreme rainfall events within the watersheds limits.

External threats considered are flooding due to failure of flood defence system of rivers and canals and inundation of roads in coastal areas combining the effects of sea level rise and storm surges.

Measures may have direct effects on the threat (applying the measures limit the threat) or indirect effects (applying the measures ensures a better knowledge of the threat or a better extreme event management).

Internal threats
Table 3 presents a list of adaptation measures and their effects on culvert capacity (overloading or obstruction) as well as on embankment's erosion due to overloading.

"Overloading of the culvert" considers an increase of the water level which may involve flooding of the road surface (3 levels as defined in chapter 2.1.4.)

Note: the measures were selected in the database by applying the filter "02-1 Overloading of hydraulic systems crossing the road in column C 'Threat sub category'.

Table 3: Adaptation measures – Internal threats

Nr	Measure	Overloading of the culvert	Obstruction of the culvert	Erosion of road embankments
Capacity building				
174	Prepare and educate road users for flooding	X	X	X
175	Prepare and educate staff for flooding	X	X	X
Legislation , regulations				
161	Establish a guideline for standardized inspection of culverts		X	X
187	Revised standards for design of culverts	X		X
188	Revised standards for road design, avoiding build-up of water level differences	X		
Maintenance and replacement				
154	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall	X	X	X
155	Clear natural blockages such as shrubs and weeds		X	X
162	Inspect and clean watercourses regularly	X	X	X
163	Inspect blue spot areas adjacent to heavy rainfalls + Inspect watercourses regularly		X	X
190	Take measures to reduce downstream sedimentation and clean debris and sediment from the outlet ditch afterwards + Remove recent accumulations of debris which create obstructions to flow + Remove large obstructions (such as fallen trees or rubbish which restrict flow	X	X	X
Monitoring				
167	Keeping records of events and locations of overloaded hydraulic systems + Keeping records of flooding events and locations	X	X	X
170	Mapping areas prone to flooding (blue spot analysis) + Carrying out risk assessment of identified areas	X	X	X
186	Reviewing design storm return periods in the light of new weather information	X		X
Planning				
149	Avoid urbanisation and watersheds diversions in vulnerable areas	X	X	X
153	Carrying out risk assessment of identified areas			
159	Develop plans and routines for the priority of securing areas prone to overloaded hydraulic systems +Develop plans and routines for the priority of securing areas prone to flooding + Make strategies for temporary rerouting + Preparing contingency/emergency plans	X	X	X
165	Keeping in-house GIS to date	X	X	X
166	Keeping records of events and locations of overloaded hydraulic systems	X	X	X
169	Make strategies for temporary rerouting	X	X	X
Resilient construction				
148	Avoid deforestation in the catchment area	X	X	X

Nr	Measure	Overloading of the culvert	Obstruction of the culvert	Erosion of road embankments
150	Build dams, reservoirs and retaining ponds to buffer the water + Construct detention storage	X		X
158	Cover slope with vegetation	X		X
172	Organize weirs/overflow towards storage facilities	X		
182 185	Resize drainage systems to meet threats + Replace the culvert with a small bridge	X	X	X
	Robust construction			
151	Build flood walls to protect the road from flooding	X		
156	Cover road embankment with geotextile			X
157	Cover slope with rock blanket			X
160	Dredge to increase depths and/or straighten the stream	X	X	X
173	Pave the inlet and the outlet of the culvert	X		X
177	Protect entrance embankment with rock blanket		X	
178	Protect entrance against floating debris		X	
181	Rebuild stretches of the road on safe ground	X	X	X
191	Wetland restoration as part of a strategy of multiply lines of flood defences	X		X
	Traffic management			
152 168 171 179 180 183 184 189	Carriageway cross-over + Lane closure + Modal shift + Real time traffic information + Real time weather and traffic forecast + Rerouting and guidance + Speed limits + Reroute the traffic	X	X	X
164	Install sign posts warning for flooding in threatened areas	X	X	X
176	Prepare Traffic Management Plans	X	X	X

External threats

Table 4 presents a list of adaptation measures and their effects on culvert capacity (overloading or obstruction) as well as on embankment's erosion due to overloading.

Note: the measures were selected in the database by applying the filter “01-3 Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges”, and “01-1 Flooding due to failure of flood defence system of rivers and canals” in column C ‘Threat sub category’.

Table 4: Adaptation measures – External threats

Nr	Measure	Overloading of the culvert	Obstruction of the culvert	Erosion of road embankments
capacity building				
20	Prepare and educate road users for flooding	X	X	X
21	Prepare and educate staff for flooding	X	X	X
legislation , regulations				
32	Revised standards for road design, avoiding build-up of water level differences	X		
maintenance and replacement				
7	Clear natural blockages such as shrubs and weeds		X	X
27 28	Remove recent accumulations of debris which create obstructions to flow + Remove large obstructions (such as fallen trees or rubbish which restrict flow	X	X	X
90	Inspect and clean watercourses regularly	X	X	X
monitoring				
16	Keeping records of flooding events and locations	X	X	X
19	Mapping areas prone to flooding (blue spot analysis) + Carrying out risk assessment of identified areas	X	X	X
110	Reviewing design storm return periods in the light of new weather information	X		X
planning				
6	Carrying out risk assessment of identified areas	X	X	X
9	Develop plans and routines for the priority of securing areas prone to flooding	X	X	X
14	Integration of infrastructure development and land use planning	X	X	X
15	Keeping in-house GIS up to date	X	X	X
18	Make strategies for temporary rerouting	X	X	X
22	Prepare contingency / emergency plans	X	X	X
research				
24	Preventive information	X	X	X
resilient construction				
2	Avoid deforestation in the catchment area	X	X	X
10	Drainage of road embankment for fast lowering of groundwater table after flood retreats			X
31	Resize drainage systems to meet threats	X	X	X
	Organize weirs/overflow towards storage facilities	X		
33	Shelter locations with facilities and life supplies, evacuation routes	X		
35	Use geosynthetics for improving slope stability and erosion protection			X
36	Use vegetation for improving slope stability and erosion protection			X
robust construction				
3	Build dams, reservoirs and retaining ponds to buffer the water	X	X	X

Nr	Measure	Overloading of the culvert	Obstruction of the culvert	Erosion of road embankments
4	Build flood walls to protect the road from flooding	X		
8	Construction of (temporary) flood barriers along road	X		
11	Dredge to increase depths and/or straighten the stream	X		X
12	Elevated roads above High Water Level	X		X
25	Rebuild stretches of the road on safe ground	X	X	X
26	Relocation of road	X	X	X
37	Wetland restoration as part of a strategy of multiply lines of flood defences	X		X
97	Mangroves restoration to reduce wave run-up and shore erosion	X		X
99	Physical reinforcement of the coast line to protect against wave action	X		X
112	Sand nourishment to reduce wave run-up and shore erosion	X		X
traffic management				
1 5 17 23 29 30 34 84 91 95 107 108 114	Access restriction + Carriageway cross-over + Lane closure + Reroute the traffic + Rerouting and guidance + Speed limits	X	X	X
13	Install sign posts warning for flooding in threatened areas	X	X	X
103	Prepare Traffic Management Plans	X	X	X

2.1.6 Step 5: Establishing a policy

The policy matrices are a rearrangement of the measures selected in the previous step in order to be grouped together according to the category of measures and the implementation stages.

The matrices were produced from the database by selecting the measures, applying the macro CTRL+y and summarized the measures when necessary.

Internal threats
Internal threats considered are the same as in the previous step: pluvial flooding, overloading of culverts and erosion of road bases due to extreme rainfall events in the watersheds limits.

Table 5 presents the measures for flooding of road surface, erosion of road embankments and overloading of hydraulic systems crossing the road.

External threats
External threats considered are the same as in the previous step: flooding due to failure of flood defence system of rivers and canals and inundation of roads in coastal areas combining the effects of sea level rise and storm surges.

Table 6 presents the measures for flooding of road surface due to inundation in coastal areas and failure of flood defence systems.

Table 5: Policy matrix for flooding of road surface, erosion of road embankments and overloading of hydraulic systems crossing the road

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme	During an extreme	Just after an extreme	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Avoid deforestation in the catchment area / Avoid urbanisation and watersheds diversions in vulnerable areas / Build dams, reservoirs and retaining ponds to buffer the water / Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to overloaded hydraulic systems / Dredge to increase depths and/or straighten the stream / Keeping in-house GIS up to date / Keeping records of events and locations of overloaded hydraulic systems / Organize weirs/overflow towards storage facilities / Pave the inlet and the outlet of the culvert / Wetland restoration as part of a strategy of multiply lines of flood defences			**EXTREME EVENT MANAGEMENT:** Modal shift / Reroute the traffic			
	Robust construction		**PREVENTION:** Cover road embankment with geotextile / Cover slope with rock blanket / Cover slope with vegetation / Protect entrance embankment with rock blanket / Protect entrance against floating debris / Rebuild stretches of the road on safe ground / Revised standards for design of culverts / Revised standards for road design, avoiding buildup of water level differences / Take measures to reduce downstream sedimentation and clean debris and sediment from the outlet ditch afterwards.					
	Legislation, regulations							
	Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Replace the culvert with a small bridge / Resize drainage systems to meet threats					
	Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT:** Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall / Clear natural blockages such as shrubs and weeds / Establish a guideline for standardized inspection of culverts / Inspect and clean watercourses regularly / Inspect blue spots areas adjacent to heavy rainfalls				
	Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Carriageway cross-over / Install sign posts warning for flooding in threatened areas / Lane closure / Make strategies for temporary rerouting / Prepare Traffic Management Plans / Real time traffic information / Real time weather and traffic forecast / Rerouting and guidance / Speed limits					
	Capacity building	**CAPACITY BUILDING:** Prepare and educate road users for flooding / Prepare and educate staff for flooding						
	Monitoring	**MONITORING AND PREDICTION:** Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Reviewing design storm return periods in the light of new weather information						
	Research							

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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Table 6: Policy matrix for flooding of road surface due to inundation in coastal areas and failure of flood defence systems

STAGES	PRO-ACTION	PREVENTION	PREPARATION				RECOVERY
			In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Avoid deforestation in the catchment area / Build dams, reservoirs and retaining ponds to buffer the water / Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to flooding / Dredge to increase depths and/or straighten the stream / Integration of infrastructure development and land use planning / Keeping in-house GIS up to date / Make strategies for temporary rerouting / Mangroves restoration to reduce wave run-up and shore erosion / Physical reinforcement of the coast line to protect against wave action / Prepare contingency / emergency plans / Sand nourishment to reduce wave run-up and shore erosion / Wetland restoration as part of a strategy of multiply lines of flood defences			**EXTREME EVENT MANAGEMENT:** Access restriction / Carriageway cross-over / Construction of (temporary) flood barriers along road / Lane closure / Reroute the traffic / Rerouting and guidance / Speed limits			
Robust construction		**PREVENTION:** Elevated roads above High Water Level / Rebuild stretches of the road on safe ground / Relocation of road / Revised standards for road design, avoiding buildup of water level differences / Shelter locations with facilities and life supplies, evacuation routes					
Legislation, regulations							
Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Drainage of road embankment for fast lowering of groundwater table after flood retreats / Resize drainage systems to meet threats / Use geosynthetics for improving slope stability and erosion protection / Use vegetation for improving slope stability and erosion protection					
Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT:** Clear natural blockages such as shrubs and weeds / Inspect and clean drainage systems regularly				**CORRECTIVE MAINTENANCE AND REPLACEMENT:** Remove large obstructions (such as fallen trees or rubbish which restrict flow / Remove recent accumulations of debris which create obstructions to flow
Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Install sign posts warning for flooding in threatened areas / Prepare Traffic Management Plans					
Capacity building	**CAPACITY BUILDING:** Prepare and educate road users for flooding / Prepare and educate staff for flooding						
Monitoring	**MONITORING AND PREDICTION:** Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Reviewing design storm return periods in the light of new weather information						
Research	**RESEARCH:** Preventive information						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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2.1.7 Step 6: Assessment of consequence criteria for measures

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts. E.g. the impact of flooding on availability is more serious than a reduction of driving ability in a heavy rainstorm.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

Internal threats
Table 48 in Annex C presents the assessment of the consequences of implementing the measures for flooding of road and erosion of road embankments due to pluvial flooding and overloading of hydraulic systems crossing the road.

External threats
Table 49 in Annex C presents the assessment of the consequences of implementing the measures for flooding of road surface due to failure of flood defence system and inundation in coastal areas.

2.1.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. 'Do minimum' strategy: a combination of the Pro-active attitude, Corrective maintenance and management, extreme event management and Traffic management policies in Table 5 and Table 6. This strategy implies regular inspection and maintenance, development of plans for securing areas prone to flooding and preparation of traffic management plans.
2. 'Future-proof designs' and 'Update operating procedures' strategies: a combination of Upgrading, Prevention and Monitoring and prediction policies of Table 5 and Table 6. This strategy implies cleaning of watercourses, replacement of undersized culverts and improvement of entrance and exit facilities, protection of inlet against floating debris and high velocities.
3. 'Monitoring' strategy: this strategy will build up a knowledge base of flooding events and areas, allowing better informed decisions for maintenance, upgrading and emergency plans as well as for reviewing design storm return periods. The monitoring may also include the socio-economic impacts of implementing or not implementing adaptation measures. This strategy thus serves the decision making between strategies, and the selection of measures in a strategy.
4. 'Research' strategy: this strategy aims at improving the measures implemented in the first two strategies with respect to cost-effectiveness, traffic hindrance, road user safety or network operation. The research may include materials and construction methods, early warning systems and socio-economic models.

At present, most NRAs adopt the 'Do minimum' strategy (emergency plan, mapping on flood risk, maintenance…), and some NRAs have started improving design guideline as part of the 'Future-proof designs' strategy (CEDR, [2]).

The decision to adopt a strategy or shift from one strategy to another can be based on the following considerations:

- The Monitoring strategy is a no-regret option that facilitates further decision making.
- In the 'Do minimum' strategy, cost-benefit studies (including socio-economic cost) will support decisions between corrective maintenance and traffic management strategies.
- For upgrading existing roads for an additional service life of 10-20 years, cost-benefit studies will help decide between only limiting increase flood by implementing appurtenant facilities in the vicinity of existing culverts, and resizing these culverts i.e. a change to the 'Future-proof designs' strategy. The selection will depend on the risk assessment studies showing the more vulnerable areas.
- For new construction of roads with service lives of 30-50 years, cost-benefit studies can support the decision to change to the 'Future-proof designs' strategy. Cost-benefit studies need to consider uncertainty explicitly, both in climate change and in traffic volume. The latter is probably most influential.

2.1.9 Step 8: Stakeholders to be involved

The main stakeholders are the **NRA** and the **road users** because flooding of road surface and erosion of embankments are at first linked with the drivers' safety and thus the reputation of the NRA.

Nevertheless the **people living around the road** are also involved because in vulnerable areas, water depth increase may cause high damages to human beings and buildings.

Regarding environmental stakes, stakeholders such as **water management authorities**, **environmental agencies**, **fishing association** and **people living around the road** should be involved. Actually, an increase of flooded area upstream has a direct impact on the people living in the vicinity of the road (decrease of agricultural activities, leisure activities…)

2.1.10 Step 9: Existing knowledge gaps

Climate variables with existing knowledge gaps

We will focus on the main climate variable, aggravating climate variables are not considered here.

As stated before (chapter 2.1.4), it is still highly difficult to predict the value of the rainfall intensity increase (model without adequate scale, temporal variable not consistent with rainfall intensities…).

The required temporal and spatial resolution of the climate variable is given below.

Table 7: Climate variables for culvert capacity

Climate variable	Unit	Temporal resolution	Spatial resolution
IDF curves	Intensity : mm/h Duration : min Frequency : month-year	Min-hr-day	Storm cell

Upcoming measures
Research needs or on-going of the NRA are (CEDR report on Climate change [2]):

- Better forecast of precipitation intensity,
- Review of the climate change costs,
- Review of design standards,
- Strengthening of climate modelling research at national and local level.

FEHRL's Resilient Road roadmap [3] can be used as input as presents projections for development, demonstration and implementation of upcoming adaptation measures, both technological and managerial.

Data to be collected in order to assess the resilience of the asset
The data that need to be collected in order to understand the current capability of the culverts and predict the future capability are given below:

- Construction records regarding:
  - Culvert features: shape, dimensions, gradient, material, inlet and outlet facilities,
  - Concerned area features: total surface area drained into the facility, mean slope, type of actual cover (impervious pavement, grassed embankment…)
- Maintenance records: date of construction, frequency of maintenance and type of debris,
- Extreme rainfall event records: type and date of malfunctioning (flood, backwater, erosion…) with rainfall records.

2.1.11 Step 10: Time to market of upcoming techniques

The FEHRL Resilient Road roadmap [3] estimates the following times to market:

- Management Strategies - New Drainage Design and Specifications – Regulatory framework 6 years, time to market 2012-2018 (6 years)
- Governing principles - Land Use Planning Maps Guiding Construction Decision - time to market 2012-2024 (12 years)

2.2 Hydraulic capacity of road drainage systems

In this chapter only surface run-off is considered, not subsurface drainage.

2.2.1 Step 0: The road owner's needs

Climate change and impacts
The CEDR report on Climate change [2] summarizes the expected climate changes during the twenty-first century.

Regarding rainfall events, contrary tendencies are expected between north and south concerning mean precipitation whereas a general increase in extreme intensity is indicated: "While annual precipitation is likely to increase in the north and decrease in the south, the intensity of daily precipitation and the probability of extreme precipitation intensities may increase in all regions".

It is important to add that predictions for mean annual amounts of rain are far better known than for extreme events. These extreme rain events are the most difficult parameter to assess with the predictions models.

Extreme rainfall intensity events will increase as a result of climate change, resulting in malfunctioning of road drainage systems:

- Overloading of storm drain systems (open or closed drains) causing flooding and erosion,
- Increase of aquaplaning due to difficult sheet flow across the pavement surface causing traffic difficulties even interruptions,
- Flooding / malfunctioning of retention / treatment ponds causing more downstream overflow and / or pollution.

In south Europe, **annual precipitation** will decrease as a result of climate change, resulting in less pollution washing which may cause less efficiency of treatment ponds.

This chapter deals with malfunctioning of road drainage systems including pavement drainage, storm drains, roadside channels and storage facilities. This impact is also referred as "**deterioration of drainage capacity of road drainage system**".

Effects of damage
The damages from higher rainfall events will cause:

- a decrease in availability due to maintenance-replacement -rehabilitation works or traffic interruption,
- a reduction in driver safety because of unexpected water on the pavement , aquaplaning, reduced visibility and sometimes traffic interruption,
- an increase in maintenance-replacement -rehabilitation cost,
- a loss of confidence of the public in the ability of the road owner to deal with climate change impacts.

The damage from decrease of annual precipitations may cause:

- an increase in environmental measures cost due to pollution at discharging points,
- a decrease in environmental sustainability due to rising pollution at discharging points from treatment ponds.

Concerns of the NRAs
The PEB members identified the following specific road owner's problems related to drainage systems:

- It is necessary to ensure sufficient drainage capacity for the remaining service life of the structure, which is XX years (to be decided by the road owner) → see chapter 2.2.8
- The design rules require a capacity corresponding to the YY-year runoff. → see chapter 2.2.3
- Data on precipitation and other factors influencing runoff are available, but their quality might not be adequate. → see chapter 2.2.10
- What kinds of climate data are needed? → see chapter 2.2.10
- What is the best way to adapt? Which adaptation technique should be applied and when? → see chapter 2.2.8

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs. Regarding drainage system capacity, we will focus on the increase of rainfall intensities. Nine out of eleven NRAs consider higher rainfall intensity as a serious risk.

The main concerns and needs are the following:

- Norway and Finland mention problems related to insufficient drainage and damage to gravel road structures,
- Several strategies-actions are already implemented in 6 countries (Norway, Sweden, Denmark, United Kingdom, Ireland and France) : increase of drainage system capacity, drainage asphalt, improved emergency plans, adapted traffic, improved planning,
- Half of the countries indicate the needs for research on: better forecast (Denmark), development of drainage systems (Ireland), influence on the design parameters of drainage systems and maintenance costs (Italy), effects of heavy rain on drainage systems and analysis of return periods for heavy rainfall according to the climate change scenarios (Spain).

2.2.2 Step 1: Definition of the relevant climate variable from design guidelines

Vulnerable asset
Increase of rainfall intensities is the most important cause of internal flooding of the road due to overloading of drainage system. According to its range, this flooding involves a serious impact on driver's safety and therefore a loss of reputation for NRA.

This impact is greater especially in cut roads where the run-off water is conveyed by facilities that can't be discharged when overloaded (sag points, cut roads, areas with concrete safety berms…).

Useful climate variables
The climate variable used for capacity design is the **intensity-duration-frequency curves** (IDF curves) presenting for different return period (frequency in year) the evolution of the rainfall intensity (mm/hr) according to the duration of the rain event (min).
The duration is usually comprised between a few minutes to one or 2 days. These curves are currently based on statistical analysis of historical and present records values.

The return period (frequency) needs to be decided by the road owner according to the acceptable risk. This return period may vary according to the type of facilities.

For collecting system and a chosen return period, the **maximum rainfall intensity** (in mm/h) from IDF curves is used to define the expected peak discharge (in m^3/s) for each drained area.
For storage facility, and as explained before a chosen return period, the volume of the facility may be defined by 2 methods using IDF curves:

- For the event that the duration involves the worst volume.
- For a chosen duration according to the specificity of the site: environmental stakes, urban or rural areas, study on historical and recent floods.

The climate variables used for calculating treatment pond efficiency are the **mean annual amount of rain** (mm) and the **number of rainy days**.

Relationship between consequences and threats
In general, the higher the rainfall intensities are, the higher the flood may be on pavement (by depth and / or duration). Nevertheless, this relationship has to be nuanced according to the type of facilities.
Regarding collecting system:

- For closed system using inlets, as soon as the intercepted capacity is overloaded, the pavement flooding occurs and may be fast.
- For open drain system such as surface water channels and swales, the design freeboard allows a safety margin before flooding.

Of course, the consequences are higher where no “escape” is provided for the run-off water.

Regarding storage system, if a spillway is provided, the facility itself is protected for ruin but the consequences may be severe downstream by increase of peak flows especially in vulnerable areas (urban area…).

Present knowledge regarding climate parameters
As summarized in the RIMAROCC guidebook, the present knowledge regarding **maximum rainfall intensity** indicates a moderate increase since the 1961-1990 period. Regarding frequency, a moderate increase has also occurred in north Europe. The qualitative foresights assess the certainty of predictions as likely e.g. above 66 % probability of occurrence. The time horizon is still quite difficult to define nevertheless some statistical evidence of trends are already observed (more extreme events since the 80s in France).

Regarding **seasonal and annual average rainfall**, a moderate to significant increase is already observed in north Europe whereas a moderate decrease is likely to happen in south Europe.

2.2.3 Step 2: Resilience of the asset in current situation

Longitudinal system
In order to know the current resilience of the longitudinal drainage system at a particular point, the road owner shall follow the steps below:

- Collect the needed site data:
    - **Geometrical data** based on measurements, topographical survey and site visit:
        - Facility features: shape, dimensions, longitudinal profile and material,
        - Concerned area features: total surface area drained into the facility, mean slope, type of actual cover (impervious pavement, grassed embankment…)

  - **Rainfall data** (IDF curves) for estimating peak flow to discharge (for example with the worldwide known rational method).
    The value of the peak flow will depend on the chosen return period and the situation we want to simulate: actual value issued of the stage design, actual value issued of the stage design with a safety margin, expected value based on predictions or chosen risk analysis. Note that the runoff-factor in rural areas increases with longer wet periods, as the retention capacity in the surroundings are occupied
- Calculate the effective drainage capacity of the facility. A simple calculation based on the worldwide known Manning equation enables to evaluate the current conveying capacity. This calculation shall be done for :
  - The drain itself considering a freeboard (depth of filling ratio).
  - The drain totally full.
  - The drain with the extra-capacity of the shoulder and / or of the emergency lane. Actually a large extra capacity is available when considering a low depth of water (a few centimetres) on a large width. This is particularly true on the last 10-20% filling of a triangular swale
- Carry out the diagnosis of the storm drain (with freeboard / totally full / extra capacity) by comparing the drainage capacities to the various peak discharges.

A diagnosis taking into account downstream condition for example is more complicated and need the use of a mathematical model. These models are not usually used for linear infrastructure but used for urban drainage system. Nevertheless in a highly vulnerable area, it is possible to implement this type of model.

Actually in France, **safety margins** are already taken into account because a large part of the storm drain systems are designed considering a **maximum filling ratio** for the design calculations (between 75% for rectangular gullies to 90% for triangular ditches in France).

Moreover in sag points the chosen return period is higher to prevent dys-functioning due to clogging or low gradients. In sag points, the same philosophy is used in the UK but with a smaller return period.

For all Europe, we can also consider than a **spare capacity** can be gain with a rigorous maintenance routine especially in vulnerable areas: sag points, cut roads, cross slope reversal.

For the entire system, it is obvious than the current resilience is higher when the system enables discharge outside of the road by mean of weirs, overflowing on embankments towards storage facilities…Nevertheless, these discharges protect the traffic lanes of the infrastructure itself thus the drivers safety but involve downstream impacts that need to be studied: embankment scour if not protected, increase of downstream peak flow, increase of flooding areas at bottom of the road.

The consequence of the threat is no more on the traffic lanes but is only moved away if nothing more is done.

Storage / treatment system
Regarding the storage facilities, the diagnosis is almost the same that before:
- Collect the needed site data :
  - **Geometrical data** based on measurements, topographical survey and site visit:
    - Facility features: dimensions, cross-sections, type of discharge limitation, type of cover, spillway features

        - Concerned area features: total surface area drained into the facility, mean slope, type of actual cover (impervious pavement, grassed embankment…)
    - **Rainfall data** (IDF curves and annual precipitations)
        - for estimating the required volume.
          The value of the volume will depend on the chosen return period and the situation we want to simulate: actual value issued of the stage design, actual value issued of the stage design with a safety margin, expected value based on predictions or chosen risk analysis
        - for estimating efficiency.
- Calculate the effective storage capacity of the facility. A simple calculation based on geometric formulas to evaluate the current volume. This calculation shall be done for :
    - The facility itself considering a freeboard (depth of filling ratio).
    - The facility totally full.
    - The facility with the spillway in action.
    - The facility with the extra-capacity only if in cut.
- Calculate the efficiency of the facility. Methods varying among Europe
- Carry out the diagnosis of the facility by comparing the available volumes-efficiency to the needed volumes-efficiency.

If there is a spillway accurately sized, the consequence of the threat has no impact on the facility itself but is only moved away (increase peak flow and / or pollution level) if nothing more is done.

2.2.4 Step 3: Resilience of the asset in possible future situations

In this step, we will focus on the rainfall intensity variable. Actually, other climate variables (temperature, sea level rise and wind) have impacts on culvert but may be consider only as aggravating factors.

Predictions for rainfall intensities
See chapter 2.1.4.

Climate change and drainage system capability
An increase of the rainfall intensity will immediately result in a rise of the peak flow discharge resulting in an increase of water depth in the storm drain.

The possible overflowing will depend on the chosen criteria at design stage especially freeboard.

Three levels are possible, the water depth increase:
- stays in the system due to freeboard (**safety margin**) → no hazard for drivers
- overflows on the shoulder / emergency lane (**extra capacity**) but not on the traffic lane → medium hazard for drivers
- submerges the traffic lane → high hazard for drivers

These 3 levels consider that there is no “escape” for the overflow (sag points, cut roads…).

Of course for extreme flood, we may assume that the traffic is not possible. In this case, the risk remains only structural.

Data to define resilience in the future
See chapter 2.1.4.

2.2.5 Step 4: Identification of applicable / appropriate adaptation measures

Methodology

External and internal threats are considered separately. For each, measures outside the road owner's easement are indicated (measure underlined in the tables). Measures that are linked to the same subject are listed together.

Internal threats considered are pluvial flooding, reduced visibility during heavy rain including splash and spray and aquaplaning in ruts due to extreme rainfall events on road surface.

External threats considered are flooding due to failure of flood defence system of rivers and canals and inundation of roads in coastal areas combining the effects of sea level rise and storm surges.

Measures may have direct effects on the threat (applying the measures limit the threat) or indirect effects (applying the measures ensures a better knowing of the threat or a better extreme event management).

Internal threats

Table 8 presents a list of adaptation measures and their effects on drainage system efficiency.

"Overloading of storm drain systems" considers an increase of the water level which may involve flooding of the road surface (3 levels as defined in chapter 2.2.4).

Note: the measures were selected in the database by applying the filter "01-2 Pluvial flooding", "06-2 Reduced visibility during snowfall, heavy rain including splash and spray " and "06-5 Aquaplaning in ruts due to precipitation on the road, splash and spray" in column C 'Threat sub category'.

Table 8: Adaptation measures – internal threats

Nr	Measure	Overloading of storm drain systems	Aquaplaning	Malfunctioning of storage / treatment ponds
	Capacity building			
64	Prepare and educate road users for flooding	X		
65	Prepare and educate staff for flooding	X		
482	Increasing self-reliance of road users	X		
486	Training of road owners for emergency situations	X		
	Legislation , regulations			
52	Establish a guideline for standardized inspection of drainage system	X		X
79 514 515	Revised standards for road design, avoiding build-up of water level differences + Revised standards for in-pavement and road edge drainage + Revised standards for materials in surface courses	X	X	X
	Maintenance and replacement			

Nr	Measure	Overloading of storm drain systems	Aquaplaning	Malfunctioning of storage / treatment ponds
45	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall	X		X
46	Clear natural blockages such as shrubs and weeds	X		X
53	Inspect blue spots areas adjacent to heavy rainfalls	X		X
54	Inspect watercourses regularly			X
58	Keeping the road drainage in good condition	X		
68	Prevent the clogging of pipes/culverts on connecting roads	X	X	X
73	Remove large obstructions (such as fallen trees or rubbish which restrict flow	X		X
74	Remove recent accumulations of debris which create obstructions to flow	X		X
481 503	Appropriate inspection and maintenance of in-pavement and road edge drainage	X	X	
Monitoring				
57	Keeping records of flooding events and locations	X	X	X
61 44	Mapping areas prone to flooding (Blue spot analysis) + Carrying out risk assessment of identified areas	X	X	X
78	Reviewing design storm return periods in the light of new weather information	X		X
Planning				
44	Carrying out risk assessment of identified areas	X	X	X
49 60 66	Develop plans and routines for the priority of securing areas prone to flooding + Make strategies for temporary rerouting + Preparing contingency/emergency plans	X	X	X
56	Keeping in-house GIS to date	X	X	X
Research				
69	Preventive information	X	X	
512	Reservoir pavements for hydrograph attenuation	X	X	X
513	Reservoir pavements for water quality improvement			X
Resilient construction				
39	Avoid deforestation in the catchment area	X		
48	Cover slope with vegetation	X		X
50	Drainage of road embankment for fast lowering of groundwater table after flood retreats	X		
63	Organize weirs/overflow towards storage facilities. Notice the multi-functionality of swales and the roadside area	X		
77	Resize drainage systems to meet threats	X	X	X
81	Use geosynthetics for improving slope stability and erosion protection	X		X
82	Use vegetation for improving slope stability and erosion protection	X		X
480	Apply porous asphalt surface course	X	X	

Nr	Measure	Overloading of storm drain systems	Aquaplaning	Malfunctioning of storage / treatment ponds
517	Systems for pavement surface drainage that are more reliable, and easier to inspect and maintain	X	X	
	Robust construction			
40	Build flood walls to protect the road from flooding	X		
47	Construct detention storages	X		
51	Dredge to increase depths and/or straighten the stream	X		
72	Rebuild stretches of the road on safe ground	X	X	X
83	Wetland restoration as part of a strategy of multiply lines of flood defences	X		
	Traffic management			
38 42 43 55 59 62 67 70 71 75 76 80	Access restriction + Carriageway cross-over + Lane closure + Modal shift + Real time traffic information + Rerouting and guidance + Reroute the traffic + Speed limits	X	X	
55	Install sign posts warning for flooding in threatened areas	X		
506	Placing warning signs (for rutting / aquaplaning)		X	
67	Prepare Traffic Management Plans	X		X

External threats
Table 9 presents a list of adaptation measures and their effects on drainage system efficiency.

Note: the measures were selected in the database by applying the filter “01-3 Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges”, and “01-1 Flooding due to failure of flood defence system of rivers and canals” in column C ‘Threat sub category’.

Table 9: Adaptation measures – external threats

Nr	Measure	Overloading of the culvert	Obstruction of the culvert	Erosion of road embankments
capacity building				
20	Prepare and educate road users for flooding	X	X	X
21	Prepare and educate staff for flooding	X	X	X
legislation , regulations				
32	Revised standards for road design, avoiding build-up of water level differences	X		
maintenance and replacement				
7	Clear natural blockages such as shrubs and weeds		X	X
27 28	Remove recent accumulations of debris which create obstructions to flow + Remove large obstructions (such as fallen trees or rubbish which restrict flow	X	X	X
90	Inspect and clean watercourses regularly	X	X	X
monitoring				
16	Keeping records of flooding events and locations	X	X	X
19	Mapping areas prone to flooding (blue spot analysis) + Carrying out risk assessment of identified areas	X	X	X
110	Reviewing design storm return periods in the light of new weather information	X		X
planning				
6	Carrying out risk assessment of identified areas	X	X	X
9	Develop plans and routines for the priority of securing areas prone to flooding	X	X	X
14	Integration of infrastructure development and land use planning	X	X	X
15	Keeping in-house GIS up to date	X	X	X
18	Make strategies for temporary rerouting	X	X	X
22	Prepare contingency / emergency plans	X	X	X
research				
24	Preventive information	X	X	X
resilient construction				
2	Avoid deforestation in the catchment area	X	X	X
10	Drainage of road embankment for fast lowering of groundwater table after flood retreats			X
31	Resize drainage systems to meet threats	X	X	X
	Organize weirs/overflow towards storage facilities	X		
33	Shelter locations with facilities and life supplies, evacuation routes	X		
35	Use geosynthetics for improving slope stability and erosion protection			X
36	Use vegetation for improving slope stability and erosion protection			X
robust construction				
3	Build dams, reservoirs and retaining ponds to buffer the water	X	X	X

Nr	Measure	Overloading of the culvert	Obstruction of the culvert	Erosion of road embankments
4	Build flood walls to protect the road from flooding	X		
8	Construction of (temporary) flood barriers along road	X		
11	Dredge to increase depths and/or straighten the stream	X		X
12	Elevated roads above High Water Level	X		X
25	Rebuild stretches of the road on safe ground	X	X	X
26	Relocation of road	X	X	X
37	Wetland restoration as part of a strategy of multiply lines of flood defences	X		X
97	Mangroves restoration to reduce wave run-up and shore erosion	X		X
99	Physical reinforcement of the coast line to protect against wave action	X		X
112	Sand nourishment to reduce wave run-up and shore erosion	X		X
traffic management				
1 5 17 23 29 30 34 84 91 95 107 108 114	Access restriction + Carriageway cross-over + Lane closure + Reroute the traffic + Rerouting and guidance + Speed limits	X	X	X
13	Install sign posts warning for flooding in threatened areas	X	X	X
103	Prepare Traffic Management Plans	X	X	X

2.2.6 Step 5: Establishing a policy

The matrices were produced from the database by selecting the measures, applying the macro CTRL+y and summarized the measures when necessary.

Internal threats

Table 10 presents the measures for flooding of road surface due to pluvial flooding in the policy matrix.

External threats

Table 11 presents the measures for flooding of road surface due to failure of flood defence system and inundation in coastal areas.

Table 10: Policy matrix for flooding of road surface due to pluvial flooding (overloading of drainage system)

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme	During an extreme	Just after an extreme	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	PRO-ACTIVE ATTITUDE: Avoid deforestation in the catchment area / Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Construct detention storages / Develop plans and routines for the priority of securing areas prone to flooding / Dredge to increase depths and/or straighten the stream / Establish a guideline for standardized inspection of drainage system / Keeping in-house GIS up to date / Make strategies for temporary rerouting / Organize weirs/overflow towards storage facilities / Prepare contingency / emergency plans / Wetland restoration as part of a strategy of multiply lines of flood defences			EXTREME EVENT MANAGEMENT: Access restriction / Carriageway cross-over / Lane closure / Modal shift / Reroute the traffic / Rerouting and guidance / Speed limits			
	Robust construction		PREVENTION: Cover slope with vegetation / Rebuild stretches of the road on safe ground / Revised standards for in-pavement and road edge drainage / Revised standards for materials in surface courses / Revised standards for road design, avoiding buildup of water level differences					
	Legislation, regulations							
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Apply porous asphalt surface course / Drainage of road embankment for fast lowering of groundwater table after flood retreats / Resize drainage systems to meet threats / Systems for pavement surface drainage that are more reliable, and easier to inspect and maintain / Use geosynthetics for improving slope stability and erosion protection / Use vegetation for improving slope stability and erosion protection					
	Maintenance and management			PREVENTIVE MAINTENANCE AND REPLACEMENT: Appropriate inspection and maintenance of in-pavement and road edge drainage / Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall / Clear natural blockages such as shrubs and weeds / Inspect blue spots areas adjacent to heavy rainfalls / Inspect watercourses regularly / Keeping the road drainage in good condition / Prevent the clogging of pipes/culverts on connecting roads				CORRECTIVE MAINTENANCE AND REPLACEMENT: Remove large obstructions (such as fallen trees or rubbish which restrict flow / Remove recent accumulations of debris which create obstructions to flow
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Install sign posts warning for flooding in threatened areas / Placing warning signs / Prepare Traffic Management Plans / Real time traffic information / Real time weather and traffic forecast					
	Capacity building	CAPACITY BUILDING: Increasing self-reliance of road users / Prepare and educate road users for flooding / Prepare and educate staff for flooding / Training of road owners for emergency						
	Monitoring	MONITORING AND PREDICTION: Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Reviewing design storm return periods in the light of new weather information						
	Research	RESEARCH: Preventive information / Reservoir pavements for hydrograph attenuation / Reservoir pavements for water quality improvement						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

Table 11: Policy matrix for flooding of road surface due to failure of flood defence system and inundation in coastal areas

STAGES	PRO-ACTION	PREVENTION	PREPARATION: In preparation of an extreme event	RESPONSE: Just before an extreme event	RESPONSE: During an extreme event	RESPONSE: Just after an extreme event	RECOVERY: After an extreme event
OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Avoid deforestation in the catchment area / Build dams, reservoirs and retaining ponds to buffer the water / Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to flooding / Dredge to increase depths and/or straighten the stream / Integration of infrastructure development and land use planning / Keeping in-house GIS up to date / Make strategies for temporary rerouting / Mangroves restoration to reduce wave run-up and shore erosion / Physical reinforcement of the coast line to protect against wave action / Prepare contingency / emergency plans / Sand nourishment to reduce wave run-up and shore erosion / Wetland restoration as part of a strategy of multiply lines of flood defences			**EXTREME EVENT MANAGEMENT:** Access restriction / Carriageway cross-over / Construction of (temporary) flood barriers along road / Lane closure / Reroute the traffic / Rerouting and guidance / Speed limits			
Robust construction		**PREVENTION:** Elevated roads above High Water Level / Rebuild stretches of the road on safe ground / Relocation of road / Revised standards for road design, avoiding buildup of water level differences / Shelter locations with facilities and life supplies, evacuation routes					
Legislation, regulations							
Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Drainage of road embankment for fast lowering of groundwater table after flood retreats / Resize drainage systems to meet threats / Use geosynthetics for improving slope stability and erosion protection / Use vegetation for improving slope stability and erosion protection					
Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT:** Clear natural blockages such as shrubs and weeds / Inspect and clean drainage systems regularly				**CORRECTIVE MAINTENANCE AND REPLACEMENT:** Remove large obstructions (such as fallen trees or rubbish which restrict flow / Remove recent accumulations of debris which create obstructions to flow
Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Install sign posts warning for flooding in threatened areas / Prepare Traffic Management Plans					
Capacity building	**CAPACITY BUILDING:** Prepare and educate road users for flooding / Prepare and educate staff for flooding						
Monitoring	**MONITORING AND PREDICTION:** Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Reviewing design storm return periods in the light of new weather information						
Research	**RESEARCH:** Preventive information						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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2.2.7 Step 6: Assessment of consequence criteria for measures

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts. E.g. the impact of flooding on availability is more serious than a reduction of driving ability in a heavy rainstorm.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

Internal threats

Table 50 in Annex C presents the assessment of the consequences of implementing the measures for flooding of road and erosion of road embankments due to pluvial flooding and overloading of hydraulic systems crossing the road.

External threats

Table 51 in Annex C presents the assessment of the consequences of implementing the measures for flooding of road surface due to failure of flood defence system and inundation in coastal areas.

2.2.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. 'Do minimum' strategy: a combination of the Pro-active attitude, preventive maintenance and management, extreme event management and Traffic management policies in Table 10 and Table 11. This strategy implies regular inspection and maintenance, development of plans for securing areas prone to flooding and preparation of traffic management plans.
2. 'Future-proof designs' and 'Update operating procedures' strategies: a combination of Upgrading, Prevention and Monitoring and prediction policies of Table 10 and Table 11. This strategy implies cleaning of drainage system, replacement of undersized storm drains and application of porous asphalt surface.
3. 'Monitoring' strategy: this strategy will build up a knowledge base of flooding events and areas, allowing better informed decisions for maintenance, upgrading and emergency plans as well as for reviewing design storm return periods. The monitoring may also include the socio-economic impacts of implementing or not implementing adaptation measures. This strategy thus serves the decision making between strategies, and the selection of measures in a strategy.
4. 'Research' strategy: this strategy aims at improving the measures implemented in the first two strategies with respect to cost-effectiveness, traffic hindrance, road user safety or network operation. The research may include reservoir pavements, early warning systems and socio-economic models.

At present, most NRAs adopt the 'Do minimum' strategy (emergency plan, maintenance…), and some NRAs have started improving drainage design guideline as part of the 'Future-proof designs' strategy (CEDR, [2]).

The decision to adopt a strategy or shift from one strategy to another can be based on the following considerations:

- The Monitoring strategy is a no-regret option that facilitates further decision making.
- In the 'Do minimum' strategy, cost-benefit studies (including socio-economic cost) will support decisions between corrective maintenance and traffic management strategies.
- For upgrading existing roads for an additional service life of 10-20 years, cost-benefit studies will help decide between only limiting increase flood by implementing weirs facilities and resizing the storm drain system i.e. a change to the 'Future-proof designs' strategy. The selection will depend on the risk assessment studies showing the more vulnerable areas.
- For new construction of roads with service lives of 30-50 years, cost-benefit studies can support the decision to change to the 'Future-proof designs' strategy. Cost-benefit studies need to consider uncertainty explicitly, both in climate change and in traffic volume. The latter is probably most influential.

2.2.9 Step 8: Stakeholders to be involved

Regarding the collecting system, the main stakeholders are the **NRA** and the **road users** because it is mostly linked with the drivers' safety and thus the reputation of the NRA.

Regarding storage-treatment facilities, stakeholders such as **water management authorities**, **environmental agencies**, **fishing association** and **people living around the road** should be involved. Actually, a change in peak flow downstream of the infrastructure or flooded area upstream has a direct impact on the people living in the vicinity of the road.

Moreover, a change in water quality has a direct impact on the nearby environment: watercourses, potable water areas, leisure activities…

2.2.10 Step 9: Existing knowledge gaps

Climate variables with existing knowledge gaps
We will focus on the main climate variable, aggravating climate variables are not considered here.

As stated before (chapter 2.2.4), it is still highly difficult to predict the value of the rainfall intensity increase (model without adequate scale, temporal variable not consistent with rainfall intensities…).

The required temporal and spatial resolution of the climate variable is given below.

Table 12: Climate variables for drainage system capacity

Climate variable	Unit	Temporal resolution	Spatial resolution
IDF curves	Intensity : mm/h Duration : min Frequency : month-year	Min-hr-day	Storm cell

Upcoming measures
Research needs or on-going of the NRA are (CEDR report on Climate change [2]):

- Review of design standards for drainage,
- Better forecast of precipitation intensity and the location of the incident
- Impact of road drainage on groundwater,
- Influence on the design parameters of drainage systems and maintenance costs,
- Effects of heavy rain on drainage systems,
- Analysis of return periods for heavy rainfall according to the climate change scenarios.

FEHRL's Resilient Road roadmap [3] can be used as input as presents projections for development, demonstration and implementation of upcoming adaptation measures, both technological and managerial.

Data to be collected in order to assess the resilience of the asset
The data that need to be collected in order to understand the current capability of the drainage system and predict the future capability are given below:

- Construction records regarding
  - Storm drains features: shape, dimensions, longitudinal profile and material,
  - Storage features: dimensions, cross-sections, type of discharge limitation, type of cover, spillway features
  - Concerned area features: total surface area drained into the facility, mean slope, type of actual cover (impervious pavement, grassed embankment…)
- Maintenance records : frequency of maintenance and type of debris
- Extreme rainfall event records: type and date of malfunctioning (flood, backwater at connecting structure, erosion…) with rainfall records.

2.2.11 Step 10: Time to market of upcoming techniques

The FEHRL Resilient Road roadmap [3] estimates the following times to market:

- Management Strategies - New Drainage Design and Specifications – Regulatory framework 6 years, time to market 2012-2018 (6 years)
- Develop New Resilient Drainage Systems – R&D 5 years, demonstration 3 years; time to market 2012-2021 (9 years)

3 Landslides, Stability and Erosion

3.1 Stability of road embankments after flooding from external sources

This chapter mainly deals with the consequences of prolonged immersion of roads, such as the reduction in bearing capacity of pavements and stability of the road embankment. The flooding originates from an area outside the road itself.

The impacts of increased precipitation on the road itself are dealt with in chapters 2.2 ‘Drainage capacity of road drainage systems’ and 3.2 ‘Slides of the embankment after heavy rain or heavy rain after dry period, landslides’. Erosion of road embankments due to high speed water flow is dealt with in chapter 3.4 ‘Erosion of road embankments’. Overloading of culverts is treated in chapter 2.1 ‘Drainage capacity of culverts’.

3.1.1 Step 0: The road owner’s needs

Relevance to the road owner
In most parts of Europe precipitation, temperatures, sea level and wind speeds will increase as a result of climate change, leading to an increased probability of flooding that jeopardizes the operation of road infrastructure:

- Flooding due to failure of flood defence system of rivers and canals, combining the effects of snowmelt in the catchment area, rainfall in the catchment area and extreme wind.
- Pluvial flooding by overland flow after precipitation, increasing groundwater levels and aquifer hydraulic heads.
- Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges
- Flooding from snowmelt by overland flow.

The consequences of flooding may be acerbated by a previous long dry period that has caused desiccation cracking of the road embankment.

The damage from the combined changes in precipitation, temperatures, sea level and wind speeds will threaten the safety of road users, reduce the availability, increase repair and maintenance cost, and cause the loss of confidence of the public in the ability of the road owner to deal with climate change impacts.

This chapter mainly deals with the impacts of prolonged immersion of roads, such as the reduction in bearing capacity of pavements and verges, stripping of binders and embankment stability.

According to the WEATHER project [23], flooding is one of the biggest climate related factors with respect to losses to road infrastructure assets, operations and fleet. The total annual cost associated with rain and flooding is estimated at 800 M€, 35% of the total cost. Cost to infrastructure assets is the largest part, amounting to 600 M€ annually.

Concerns of the NRAs
The PEB members identify the following specific road owner’s problems related to stability of road embankments after flooding from external sources:

- Are embankments and road constructions stable when flooded, does this depend on flooding time?
- Embankments should be fit to handle both flooding and long term drought followed by heavy rain. Does this mean design and construction have to be changed?

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs with respect to stability of road embankments after flooding from external sources:

- Better flood projections, better projections of intense rainfall, better predictions of sea-level rise and storm surge
- Development of engineering methods for avoiding floods: e.g. retention ponds.
- Production of new elevation data from laser scanning for better flooding maps.
- Simulations of hydrological models coupled to regional climate models.
- Reconstruction of series of floods in the past and their analysis.

Impacts

Most flooding related damage concerns:

- Bearing capacity of pavements.
- Bearing capacity of unpaved verges.
- Stripping / ravelling of asphalt surface courses.
- Embankment stability.

Bearing capacity of pavements: Most subgrade and road base materials will lose a significant part of their strength and stiffness when saturated. Consequently, stresses in the structural pavement layers under traffic loading will be much larger than in non-saturated conditions, and the passage of even a few heavy vehicles is sufficient to cause severe cracking of the pavement. In the aftermath of hurricane Katrina, all size and weight restrictions for emergency, repair and debris hauling vehicles were relieved. Because the ground was still saturated, the heavy traffic caused great damage to the roads in the New Orleans area, much more than the actual flooding itself [24].

Bearing capacity of unpaved verges: Saturation of materials in the verge will cause a marked reduction in bearing capacity as compared to the normal condition.

Stripping and ravelling of asphalt surface course: Asphaltic surface courses that are exposed to water will generally start losing aggregates prematurely through a damage mechanism known as stripping or ravelling.

Embankment stability: An increase in pore pressure will reduce the strength of coarse granular materials, potentially leading to failure of embankment slopes. Seepage forces along slopes after falling of the water level will also compromise slope stability. Erosion by water seeping from a saturated embankment and flow through desiccation cracks may undermine the embankment.

3.1.2 Step 1: Definition of the relevant climate variable from design guidelines

Table 13 lists the design models and climate parameters for deterioration mechanisms related to flooding.

Table 13: Design models and climate parameters

Deterioration mechanism	Design model	Climate parameter
Flooding due to failure of flood defence system of rivers and canals	-	Snowmelt, rainfall in the catchment area, extreme wind speed, wind direction
Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)	-	Extreme rainfall events (heavy showers, long periods of rain)
Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges	-	Sea level rise, extreme wind speed, wind direction (-> storm surge)
Flooding from snow melt (overland flow after snow melt)	-	Temperature
Bearing capacity of pavements	ME-PDG [6], [7]	Precipitation, higher temperatures, sea level rise, wind speed → Degree of saturation of subgrade an road base materials
Bearing capacity of verges	E.g. Terzaghi-Meyerhof type models [28]	Precipitation, higher temperatures, sea level rise, wind speed → Degree of saturation of verge materials
Stripping and ravelling of asphalt surface course	RoAM [29]	Precipitation, higher temperatures, sea level rise, wind speed → Water content of binder
Embankment stability	E.g. Bishop slip circle analysis [28]	Precipitation, higher temperatures, sea level rise, wind speed → Pore pressures in embankment, ground water flow

Relevant climate parameters are one or more of the following:

- Precipitation in the area around the construction, both extreme rainfall events (heavy showers) and long periods of rain.
- Precipitation in the catchment area of rivers near the construction.
- Higher temperatures causing snow melt in the catchment area of rivers near the construction.
- Sea level rise and storm surge by wind near the construction.

Flooding may have impacts on design of culverts, drains, bridges, erosion protection, landslide protection, bearing capacity of pavements and stability of embankments.

Current design guidelines for bearing capacity of pavements and stability of embankments are lacking specifications for the performance during and after flooding.

3.1.3 Step 2: Resilience of the asset in current situation

Because pavements and embankments have not been designed for prolonged immersion after flooding, the resilience in the current situation is low.

Bearing capacity of pavements

The amount of damage inflicted to a pavement depends on construction intrinsic properties such as type of materials and layer thicknesses, degree of saturation of road base and subgrade, and number and magnitude of traffic loads. In the design condition, the degree of saturation is controlled by capillary rise from the ground water table and infiltration of precipitation. During flooding, water will infiltrate the subgrade and road base through the verges and slopes of the road embankment. Also, water will enter the road base through cracks and joints in the pavement.

Louisiana Transport Research Center (LTRC) undertook research on the impact of hurricane Katrina on roadways in the New Orleans Area [24]. Approximately 3,200 km of roads were flooded for up to five weeks. The bearing capacity of 380 km of these roads was investigated five weeks after the water retreated. Conclusions from this study are:

- Overall, pavements that were submerged were found to be weaker than non-submerged pavements, for each of the pavement strength parameters investigated.
- Concrete pavements demonstrated little relative loss of strength between those pavements that were submerged and the non-submerged pavements.
- The duration of submergence was not a factor for weakening of the asphalt pavements.
- The overall equivalent strength loss for the asphalt pavements is similar to 0.05 m (2 inches) of new asphalt concrete. The strength loss is larger in thinner pavements than in thicker pavements.
- The composite pavements demonstrated no need for additional structure in the pavement layers due to submergence.

These finding should be treated conservatively and reflect local practices and materials. The effects of road base saturation are acerbated if the pavement is cracked or jointed. Traffic load across cracks and joints causes pumping erosion of the road base, leading to a loss of bearing capacity and further deterioration.

The effects of saturation of the subgrade and road base may be compared to the situation after spring thaw, when subgrade and road base are saturated with water that is confined by frozen and impermeable subsoil. Guidelines for spring thaw resilient design of pavements may apply to roads that are subject to frequent flooding [26]. Consequently, spring thaw resilient roads will also be more resilient to flooding.

The current approach to counter the loss of bearing capacity after flooding is to close the road for a certain period after the water level has dropped, or impose weight restrictions.

Bearing capacity of unpaved verges

Saturation of materials in the verge will cause a marked reduction in bearing capacity as compared to the normal condition. Trafficability for even light vehicles wandering off the road will be seriously compromised.

Stripping and ravelling of asphalt surface course

Asphaltic surface courses that are exposed to water will generally start losing aggregates prematurely through a damage mechanism known as stripping or ravelling. Stripping is attributed to water infiltration into the asphaltic mixture, causing a weakening of the mastic and the aggregate-mastic bond. This initial stripping rapidly progresses into a more severe ravelling of the surface course, and ultimately leads to pothole forming.

Twenty days of submersion are sufficient for a small increase of the water content of binders, causing a 30% decrease in strength and stiffness [26], [27].

Embankment stability
Slope stability analyses show that the stability of the embankment slopes during the rise of the water level and the submersion of the road will not be less than in dry conditions. During falling water the stability will be less than in dry conditions and possibly critical, due to seepage pressures along the slopes. Also, water seeping from permeable locations in the slopes may carry embankment material, thus eroding the embankment. Seepage forces may detach the cover layer from the embankment core. The probability of both mechanisms depends on the permeability of materials used in the embankment and the rate that the water level is falling.

Desiccation cracks in the embankment will partly close during flooding. However, water flow in the embankment will preferentially follow the paths along the former cracks, and may erode the embankment from within.

Finally, unprotected and unvegetated slopes in material that is sensitive to dispersion may disintegrate after some time, even in stagnant water.

3.1.4 Step 3: Resilience of the asset in possible future situations
An increase in the frequency of flooding because of climate change will affect pavements and embankments through the same mechanisms as in the current situation. The probability of repeated flooding during the service life of the road will increase.

Bearing capacity
According to current mechanistic-empirical design models the effects of repeated loads of different intensity can be added. This implies that the effects of repeated flooding on a pavement can be assessed, provided the correct properties of the saturated materials and the correct traffic loads during or just after flooding are known. According to these models, damage to the pavement does not depend on the duration of flooding, only on the amount and weight of the traffic during or just after flooding. The research on the impact of hurricane Katrina on roadways in the New Orleans Area [24] arrives at a similar conclusion, although the subgrade modulus appeared to decrease with the duration of the flooding.

However, the findings in the post-Katrina study may not be valid for all conditions and materials. The report of the 2012 FEHRL US scanning tour [24] identifies residual strength following flooding and flood resistant pavements as a research need.

An example of a similar approach is given in [26] for design of spring thaw resilient roads. This Danish approach deals with seasonal variations (representing variations in water content) by adjusting the expected bearing capacity (stiffness) of each pavement layer.

Bearing capacity of unpaved verges
The bearing capacity of coarse granular materials in verges will be fully restored after the water levels fall. Fine grained materials may exhibit swell during flooding, causing a permanent loss of compaction and bearing capacity.

Stripping and ravelling of asphalt surface course
More frequent flooding and precipitation in the future implies an increase in stripping and ravelling in the surface course.

Embankment stability
The stability of embankments is not affected by repeated flooding, provided the material properties, integrity and geometry remain the same as in the newly built embankment. Inspection and corrective maintenance after flooding will be necessary to verify that the embankments can perform in the next flood.

Fine grained materials may be susceptible to swelling and shrinking, causing deformations of the embankment and pavement upon flooding. Prolonged dry periods may cause desiccation cracks, creating preferential flow paths and exposing the embankment to erosion.

Erosion by water seeping from a saturated embankment or by flow in cracks may undermine the embankment. Erosion may alter the geometry of the embankment and make it less stable. Detachment of the cover layer in an earlier flood will leave the embankment core exposed to erosion in the next flood.

3.1.5 Step 4: Identification of applicable / appropriate adaptation measures

Table 14 presents a list of adaptation measures for stability of road embankments after flooding from external sources, with respect to the damage mechanisms.

Note: the measures were selected in the database by applying the filter ’01-1 01-1 flooding due to failure of flood defence system of rivers and canals’ AND ‘01-2 Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)’ AND ‘01-3 Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges’ AND ‘01-4 Flooding from snow melt (overland flow after snow melt)’ AND ‘04-1 Impact on soil moisture levels, affecting the structural integrity of roads, bridges and tunnels’ in column C ‘Specific threat’. Double entries for different causes of flooding have been omitted.

Table 14: Adaptation measures

Nr	Measure	Flooding	Bearing capacity of pavements	Bearing capacity of verges	Stripping and ravelling of asphalt surface course	Embankment stability
Capacity building						
20	Prepare and educate road users for flooding	X				
21	Prepare and educate staff for flooding	X				
Legislation , regulations						
32	Revised standards for road design, avoiding build-up of water level differences					X
52	Establish a guideline for standardized inspection of drainage system	X	X	X		X
358	Revised standards for binder course, (sub)base and subgrade materials, drainage			X	X	
Maintenance and replacement						
7	Clear natural blockages such as shrubs and weeds	X				

Nr	Measure	Flooding	Bearing capacity of pavements	Bearing capacity of verges	Stripping and ravelling of asphalt surface course	Embankment stability
27	Remove large obstructions (such as fallen trees or debris) which restrict flow	X				
28	Remove recent accumulations of debris or ice which create obstructions to flow	X				
45	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall or snow melt	X				
53	Inspect blue spots areas adjacent to heavy rainfall or snow melt	X				
54	Inspect watercourses regularly	X				
58	Keeping the road drainage in good condition	X				
68	Prevent the clogging of pipes/culverts on connecting roads	X				
90	Inspect and clean drainage systems regularly	X				
141	Remove snow and ice from the road	X				
	Monitoring					
16	Keeping records of flooding events and locations	X				
19	Mapping areas prone to flooding (Blue spot analysis)	X				
78	Reviewing design storm return periods in the light of new weather information	X				
353	Monitoring to detect potential problem areas, establish cause-impact relationships; maintain specific construction and maintenance records		X	X	X	X
552	Monitoring of water levels in the road embankment after flooding		X	X		X
	Planning					
6	Carrying out risk assessment of identified areas	X				
9	Develop plans and routines for the priority of securing areas prone to flooding	X				
14	Integration of infrastructure development and land use planning	X				
15	Keeping in-house GIS up to date	X				
18	Make strategies for temporary rerouting	X				
22	Prepare contingency / emergency plans	X				
	Research					
24	Preventive information	X				
344	Develop binders that are more resilient to stripping				X	

Nr	Measure	Flooding	Bearing capacity of pavements	Bearing capacity of verges	Stripping and ravelling of asphalt surface course	Embankment stability
347	Improved models for bearing capacity of pavements after flooding		X			
348	In situ strengthening of granular (sub)bases and subgrade soils, using artificial or natural cements		X			
	Resilient construction					
2	Avoid deforestation in the catchment area	X				
10	Drainage of road embankment for fast lowering of groundwater table after flood retreats	X				
31	Resize drainage systems to meet threats	X				
33	Shelter locations with facilities and life supplies, evacuation routes	X				
35	Use geosynthetics for improving slope stability and erosion protection					X
36	Use vegetation for improving slope stability and erosion protection					X
48	Cover slope with vegetation					X
63	Organize weirs/overflow towards storage facilities	X				
88	Drainage of road embankment for fast lowering of groundwater table after flood retreats		X	X		X
343	Application of geotextiles in (sub)base		X			
349	Increase the thickness of structural layers		X			
	Robust construction					
3	Build dams, reservoirs and retaining ponds to buffer the water	X				
4	Build flood walls to protect the road from flooding	X				
8	Construction of (temporary) flood barriers along road	X				
11	Dredge to increase depths and/or straighten the stream	X				
12	Elevated roads above High Water Level	X				
25	Rebuild stretches of the road on safe ground	X				
26	Relocation of road	X				
37	Wetland restoration as part of a strategy of multiply lines of flood defences	X				
47	Construct detention storages	X				
97	Mangroves restoration to reduce wave run-up and shore erosion	X				

Nr	Measure	Flooding	Bearing capacity of pavements	Bearing capacity of verges	Stripping and ravelling of asphalt surface course	Embankment stability
99	Physical reinforcement of the coast line to protect against wave action	X				
112	Sand nourishment to reduce wave run-up and shore erosion	X				
346	Improving drainage of the area	X				
351	Lowering the groundwater table within the road embankment with deeper drainage		X	X		X
Traffic management						
1 5 17 23 29 30 34 84 91 95 107 108 114	Access restriction + Carriageway cross-over + Lane closure + Reroute the traffic + Rerouting and guidance + Speed limits	X				
13	Install sign posts warning for flooding in threatened areas	X				
23	Prepare Traffic Management Plans	X				
70 71	Real time weather and traffic forecast + Real time traffic information	X				

3.1.6 Step 5: Establishing a policy

Table 15 to Table 19 present the policy matrices with the measures for Flooding of road surface (assuming no traffic is possible), for flooding from different sources, and for the impact of flooding on soil moisture levels, affecting the structural integrity of roads.

The matrices were produced from the database by selecting the ‘Threat sub category’ first in column C and then applying the macro CTRL+y.

Table 15: Policy matrix for Flooding of road surface (assuming no traffic is possible) – Flooding due to failure of flood defence system of rivers and canals

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme	During an extreme	Just after an extreme	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Avoid deforestation in the catchment area / Build dams, reservoirs and retaining ponds to buffer the water / Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to flooding / Dredge to increase depths and/or straighten the stream / Integration of infrastructure development and land use planning / Keeping in-house GIS up to date / Make strategies for temporary rerouting / Prepare contingency / emergency plans / Wetland restoration as part of a strategy of multiply lines of flood defences			**EXTREME EVENT MANAGEMENT:** Access restriction / Carriageway cross-over / Construction of (temporary) flood barriers along road / Lane closure / Reroute the traffic / Rerouting and guidance / Speed			
	Robust construction		**PREVENTION:** Elevated roads above High Water Level / Rebuild stretches of the road on safe ground / Relocation of road / Revised standards for road design, avoiding buildup of water level differences / Shelter locations with facilities and life supplies, evacuation routes					
	Legislation, regulations							
	Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Drainage of road embankment for fast lowering of groundwater table after flood retreats / Resize drainage systems to meet threats / Use geosynthetics for improving slope stability and erosion protection / Use vegetation for improving slope stability and erosion protection					
	Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT:** Clear natural blockages such as shrubs and weeds				**CORRECTIVE MAINTENANCE AND REPLACEMENT:** Remove large obstructions (such as fallen trees or rubbish which restrict flow / Remove recent accumulations of debris which create obstructions to flow
	Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Install sign posts warning for flooding in threatened areas / Prepare Traffic Management Plans					
	Capacity building	**CAPACITY BUILDING:** Prepare and educate road users for flooding / Prepare and educate staff for flooding						
	Monitoring	**MONITORING AND PREDICTION:** Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis)						
	Research	**RESEARCH:** Preventive information						

‘Do minimum’ and ‘Develop contingency plans’ strategy
‘Future-proof designs’, ‘Retrofit solutions’ and ‘Update operating procedures’ strategies
‘Monitoring’ strategy
‘Research’ strategy

Table 16: Policy matrix for Flooding of road surface (assuming no traffic is possible) – Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme	During an extreme	Just after an extreme	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	PRO-ACTIVE ATTITUDE: Avoid deforestation in the catchment area / Build flood walls to protect the road from flooding / Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Construct detention storages / Develop plans and routines for the priority of securing areas prone to flooding / Dredge to increase depths and/or straighten the stream / Establish a guideline for standardized inspection of drainage system / Keeping in-house GIS up to date / Make strategies for temporary rerouting / Organize weirs/overflow towards storage facilities / Prepare contingency / emergency plans / Wetland restoration as part of a strategy of multiply lines of flood defences			EXTREME EVENT MANAGEMENT: Access restriction / Carriageway cross-over / Carriageway cross-over / Lane closure / Modal shift / Reroute the traffic / Rerouting and guidance / Speed limits			
	Robust construction		PREVENTION: Cover slope with vegetation / Rebuild stretches of the road on safe ground / Revised standards for road design, avoiding buildup of water level differences					
	Legislation, regulations							
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Drainage of road embankment for fast lowering of groundwater table after flood retreats / Resize drainage systems to meet threats / Use geosynthetics for improving slope stability and erosion protection / Use vegetation for improving slope stability and erosion protection					
	Maintenance and management			PREVENTIVE MAINTENANCE AND REPLACEMENT: Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall / Clear natural blockages such as shrubs and weeds / Inspect blue spots areas adjacent to heavy rainfalls / Inspect watercourses regularly / Keeping the road drainage in good condition / Prevent the clogging of pipes/culverts on connecting roads				CORRECTIVE MAINTENANCE AND REPLACEMENT: Remove large obstructions (such as fallen trees or rubbish which restrict flow / Remove recent accumulations of debris which create obstructions to flow
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Install sign posts warning for flooding in threatened areas / Prepare Traffic Management Plans / Real time traffic information / Real time weather and traffic forecast					
	Capacity building	CAPACITY BUILDING: Prepare and educate road users for flooding / Prepare and educate staff for flooding						
	Monitoring	MONITORING AND PREDICTION: Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Reviewing design storm return periods in the light of new weather information						
	Research	RESEARCH: Preventive information						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

Table 17: Policy matrix for Flooding of road surface (assuming no traffic is possible) – Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme	During an extreme	Just after an extreme	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to flooding / Integration of infrastructure development and land use planning / Keeping in-house GIS up to date / Make strategies for temporary rerouting / Mangroves restoration to reduce wave run-up and shore erosion / Physical reinforcement of the coast line to protect against wave action / Prepare contingency / emergency plans / Sand nourishment to reduce wave run-up and shore erosion / Wetland restoration as part of a strategy of multiply lines of flood defences			**EXTREME EVENT MANAGEMENT:** Access restriction / Construction of (temporary) flood barriers along road / Lane closure / Reroute the traffic / Rerouting and guidance / Speed limits			
	Robust construction		**PREVENTION:** Elevated roads above High Water Level / Rebuild stretches of the road on safe ground / Relocation of road / Revised standards for road design, avoiding buildup of water level differences / Shelter locations with facilities and life supplies, evacuation routes					
	Legislation, regulations							
	Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Drainage of road embankment for fast lowering of groundwater table after flood retreats / Resize drainage systems to meet threats / Use geosynthetics for improving slope stability and erosion protection / Use vegetation for improving slope stability and erosion protection					
	Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT:** Inspect and clean drainage systems regularly				
	Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Install sign posts warning for flooding in threatened areas / Prepare Traffic Management Plans					
	Capacity building	**CAPACITY BUILDING:** Prepare and educate road users for flooding / Prepare and educate staff for flooding						
	Monitoring	**MONITORING AND PREDICTION:** Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Reviewing design storm return periods in the light of new weather information						
	Research	**RESEARCH:** Preventive information						

‘Do minimum’ and ‘Develop contingency plans’ strategy
‘Future-proof designs’, ‘Retrofit solutions’ and ‘Update operating procedures’ strategies
‘Monitoring’ strategy
‘Research’ strategy

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Table 18: Policy matrix for Flooding of road surface (assuming no traffic is possible) – Flooding from snow melt (overland flow after snow melt)

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme	During an extreme	Just after an extreme	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Construct detention storages / Develop plans and routines for the priority of securing areas prone to flooding / Dredge to increase depths and/or straighten the stream / Keeping in-house GIS up to date / Make strategies for temporary rerouting / Prepare contingency / emergency plans / Wetland restoration as part of a strategy of multiply lines of flood defences			**EXTREME EVENT MANAGEMENT:** Access restriction / Reroute the traffic			
	Robust construction		**PREVENTION:** Rebuild stretches of the road on safe ground					
	Legislation, regulations							
	Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Drainage of road embankment for fast lowering of groundwater table after flood retreats / Resize drainage systems to meet threats / Use geosynthetics for improving slope stability and erosion protection / Use vegetation for improving slope stability and erosion protection					
	Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT:** Cleaning out watercourses and structures of flood prone areas ahead of predicted snow melt / Clear natural blockages such as shrubs and weeds / Inspect blue spots areas adjacent to snow melt / Inspect watercourses regularly				**CORRECTIVE MAINTENANCE AND REPLACEMENT:** Remove large obstructions (such as fallen trees or rubbish which restrict flow / Remove recent accumulations of debris and ice which create obstructions to flow / Remove snow and ice from the road
	Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Install sign posts warning for flooding in threatened areas					
	Capacity building	**CAPACITY BUILDING:** Prepare and educate road users for flooding / Prepare and educate staff for flooding						
	Monitoring	**MONITORING AND PREDICTION:** Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Reviewing design storm return periods in the light of new weather information						
	Research	**RESEARCH:** Preventive information						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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Table 19: Policy matrix for Impact of flooding on soil moisture levels, affecting the structural integrity of roads, bridges and tunnels

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
	OBJECTIVES	Enable smooth and safe traffic		Support disaster consequence reduction	Evacuation route, life supply route	Minimizing loss of functions	Supply route for repairs and humanitarian aid	Supply route for recovery of affected area
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE							
	Robust construction		PREVENTION: Improving drainage of the area / Lowering the groundwater table within the road embankment with deeper drainage / Revised standards for binder course, (sub)base and subgrade materials, drainage					
	Legislation , regulations							
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Application of geotextiles in (sub)base / Increase the thickness of structural layers					
	Maintenance and management			PREVENTIVE MAINTENANCE AND REPLACEMENT: Keeping the road drainage in good condition				CORRECTIVE MAINTENANCE AND REPLACEMENT: Full depth patches
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Access restriction / Modal shift / Real time traffic information / Real time weather and traffic forecast / Rerouting and guidance					
	Capacity building							
	Monitoring	MONITORING AND PREDICTION: Monitoring to detect potential problem areas, establish cause-impact relationships; maintain specific construction and maintenance records / Monitoring of water levels in the road embankment after flooding						
	Research	RESEARCH: Develop binders that are more resilient to stripping / Improved models for bearing capacity of pavements after flooding / In situ strengthening of granular (sub)bases and subgrade soils, using artificial or natural cements / Preventive information						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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3.1.7 Step 6: Assessment of consequence criteria for measures

Table 52 to Table 56 in Annex C present the assessment of the consequences of implementing the measures for Flooding of road surface (assuming no traffic is possible), for flooding from different sources, and for the impact of flooding on soil moisture levels, affecting the structural integrity of roads.

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts. E.g. the impact of flooding on availability is more serious than a reduction of driving ability in a heavy rainstorm.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

3.1.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. 'Do minimum' strategy: a combination of the 'Preventive maintenance and management', 'Corrective maintenance and management', 'Extreme event management' and 'Traffic management 'policies of Table 15 to Table 19. The 'Preventive maintenance and management' and 'Corrective maintenance and management' policies imply that drainage systems are well maintained before the flooding season to limit the impact of flooding, and during flooding to limit the duration of the disruption. The interval of time between maintenance actions may need to be decreased as climate change progresses. The 'Extreme event management' and 'Traffic management' policies aims to preserve road user safety and limit the impact of flooding on network operation.
   The additional cost of this strategy will be relatively limited, but the impacts of flooding on availability of the network and road user safety may be very severe.
2. 'Development of contingency plans' and 'Update operating procedures' strategies: a combination of the 'Pro-active attitude', and 'Capacity building' policies of Table 15 to Table 19. The 'Pro-active attitude' focusses on preparing for flooding, for instance through the preparation of contingency plans, risk analysis or better planning of infrastructure in relation to the probability of flooding. 'Capacity building' of NRA staff and road users reinforces the 'Pro-active attitude' policy. The actual flood protection is not the task of the NRA, but the NRA will participate in emergency and evacuation schemes of regional authorities.
   The additional cost of this strategy will be relatively limited, and the impact of flooding on availability of the network will still be very severe. As compared to the 'Do minimum' strategy, the main focus of this strategy is on increasing road user safety.
3. 'Future-proof designs' and 'Retro fit solutions' strategies: a combination of 'Prevention' and 'Upgrade, retrofit and new construction' policies of Table 15 to Table 19. The 'Prevention' policy implies relocating road stretches or changing design standards to eliminate the vulnerability to flooding. The 'Upgrade, retrofit and new construction' policy implies installation of retrofit provisions to improve drainage or increase road embankment stability. This strategy reduces both vulnerability to flooding and its consequences. There may be a considerable cost increase for relocating roads and installation of retrofit provisions.
4. 'Monitoring' strategy: this strategy will build up a knowledge base of flooding events and the impacts on road infrastructure, allowing better informed decisions for extreme event management, prevention and retrofitting. The monitoring may also include the socio-

economic impacts of implementing or not implementing adaptation measures. This strategy thus serves the decision making between strategies, and the selection of measures in a strategy.

5. 'Research' strategy: this strategy aims at improving the measures implemented in the 'Future proof designs' and 'Update operating procedures' with respect to cost-effectiveness and effect on network operations. The research may include non-destructive monitoring methods, early warning systems and socio-economic models.

The approach of the NRA to flooding may depend on the probability of flooding. The flooding probability in densely populated areas well protected by flood defences may be as low as 1/1000 years, such as in the western part of the Netherlands. In scarcely populated remote areas some road stretches may flood every spring. The paper by Koetsier e.a. [30] discusses the different strategies adopted in the Netherlands Rhine delta and the Vietnamese Mekong delta.

In areas with very low probability of flooding, the focus will be on the 'Development of contingency plans' and 'Update operating procedures' strategies. Because of the very high cost of eliminating the vulnerability of the road infrastructure, it is accepted that flooding will have very severe consequences.

In areas with frequent flooding, the focus will be on 'Future-proof designs' and 'Retro fit solutions' to limit damage and disruption. Contingency plans and capacity building are part of normal operation.

The decision to adopt a strategy or shift from one strategy to another can be based on the following considerations:

- The Monitoring strategy is a no-regret option that facilitates further decision making. It will only be effective in areas with relatively frequent flooding.
- The impact of flooding will depend on many site and construction specific factors and uncertainty in climate change projections. All decisions should therefore be based on impact studies considering all these factors.
- There should be a clear understanding of the role of the network during a flooding event with respect to services provided to the surrounding area. A socio-economic study will determine the criticality of parts of the network, i.e. the consequences to society during and after flooding of a part of the road network.
- Decisions between the 'Do minimum' strategy →'Development of contingency plans' and 'Update operating procedures' strategies →'Future-proof designs' and 'Retro fit solutions' strategies should be based on risk = probability of flooding x consequences.
- The best location of new infrastructure in flood-prone areas is best chosen on the basis of integral study of socio-economic development, mobility needs and risk of flooding.
- For new constructions, cost-benefit studies can support the decision to change to the 'Future-proof designs' strategy. Cost-benefit studies need to consider uncertainty in climate change explicitly.
- Cost-benefit studies for specific innovative measures can be initiated as part of the 'Research' strategy.

3.1.9 Step 8: Stakeholders to be involved

The main stakeholder is the NRA. Funding agencies need to be aware of the additional cost for adaptation, and the impacts of the 'Do minimum' and 'Development of contingency plans' and 'Update operating procedures' strategies.

Regional water management authorities are responsible for flood protection and drainage of the area surrounding the road. Regional authorities are responsible for emergency coordination and evacuation. Land use planning by local and regional authorities interacts with the need for road infrastructure and flood protection.

3.1.10 Step 9: Existing knowledge gaps

Climate variables
The relevant climate variables and the required temporal and spatial resolution are given in Table 20, for uplift of tunnels or light weight construction materials by increasing groundwater levels.

Table 20: Climate variables for Stability of road embankments after flooding from external sources

Cause of flooding	Climate variable	Unit	Temporal resolution	Spatial resolution
Flooding due to failure of flood defence system of rivers and canals	Temperature (in the catchment area)	˚C and number of (consecutive) days	hours-days	100 km
	Rainfall (in the catchment area)	mm/d	several days - week	100 km
	Extreme wind speed, wind direction	m/s	hours-days	10 km
Pluvial flooding (overland flow after precipitation, increase of groundwater levels, increase of aquifer hydraulic heads)	Extreme rainfall events (heavy showers)	mm/h	5-60 min	10 km
	Extreme rainfall events (long periods of rain)	mm/d	several days - week	10 km
Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges	Sea level rise	cm	day	100 km
	Extreme wind speed, wind direction (-> storm surge)	m/s	hours-days	10 km
Flooding from snow melt (overland flow after snow melt)	Temperature	˚C and number of (consecutive) days	days-weeks	10 km

Projections for these climate variables need to be available at the correct temporal and spatial resolution.

Upcoming measures
Measures in the Research category of the database are:

- Develop binders that are more resilient to stripping
- Improved models for bearing capacity of pavements after flooding
- Preventive information: early warning, monitoring and prediction systems for bearing capacity and embankment integrity.

These measures apply to all sources of flooding.

The CEDR study [2] identifies the following research needs:

- Better projections of intense rainfall, sea-level rise and storm surge
- Better simulations of hydrological models coupled to regional climate models for flood projections
- Production of new elevation data.

Data to be collected in order to assess the resilience of the asset
The data that need to be collected in order to understand the current capability of the asset and predict the future capability are given below.

- Construction records: age of surface and base course; thickness of pavement, foundation and embankment layers, type of materials and material properties, natural subsoil, geometry of embankment, type and capacity of surface and embankment drainage systems, depth to groundwater table, as-built construction drawings
- Inspection and maintenance records: rate of development of cracking of pavements, remaining service life of pavements, deterioration of drainage system capacity, performance under past floods, bearing capacity of verge, condition of surface cover of slopes
- Monitoring records: time, location and duration of past floods
- Records of climate variables

3.1.11 Step 10: Time to market of upcoming techniques

The technology readiness level (TRL) of the measures is estimated as:

- Develop binders that are more resilient to stripping – TRL 4-5: component tested in laboratory – relevant environment
- Improved models for bearing capacity of pavements after flooding – TRL 6: prototype demonstrated in relevant environment
- Preventive information : early warning, monitoring and prediction systems for bearing capacity and embankment integrity – TRL 6: prototype demonstrated in relevant environment

The FEHRL Resilient Road roadmap [3] estimates the following times to market:

- Develop binders that are more resilient to stripping – R&D 9 years, demonstration 2 years; time to market 2012-2023 (11 years)
- Improved models for bearing capacity of pavements after flooding – R&D 6 years, demonstration 3 years; time to market 2012-2021 (9 years)
- Preventive information : early warning, monitoring and prediction systems for bearing capacity and embankment integrity – R&D 5 years, demonstration 5 years; regulatory framework 3 years; time to market 2012-2025 (13 years)

3.2 Slides of the embankment after heavy rain / heavy rain after dry period / landslides

3.2.1 Step 0: The road owner's needs

Relevance to the road owner
As a result of climate change, temperatures and precipitation will change all over Europe and increasing the possibility of landslides and related hazards. Examples of impacts to be expected are:

- Slides of the road embankment/slopes above the road due to extreme rainfall events or rain after drought.
- Debris flow hitting the road due to extreme rainfall events
- Rock falls hitting the road due to extreme rainfall events and/or temperature zero-crossings.
- Snow avalanches hitting the road due to heavy snowfall and/or temperature zero-crossings

This chapter deals with damage due to hazards identified above. The hazards are also commonly referred to as "landslips and avalanches".

All types of landslips and avalanches may have a considerably negative impact on both the specific site and on the extended road network with loss of lives and traffic hindrances as possible risks.

Concerns of the NRAs
The PEB members identified the following specific road owner's problems related to landslips and avalanches in a changed climate:

- How can one identify new potential slide areas? → ROADAPT Guideline part B 'Guideline for performing a quick scan on risk due to climate change' [38].
- How can one prioritise which areas to be monitored? → chapter 3.2.7.

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs. Five out of eleven NRAs, all in the Nordic countries and around the Alps, consider landslides as a serious risk. One NRA (Norway) considers avalanches to be a serious risk. The task group, as well NRAs of Norway and Spain calls methods to analyse the relationship between heavy precipitation and landslides.

3.2.2 Step 1: Definition of the relevant climate variable from design guidelines

Landslides: Extreme rainfall events (either intense or over a long period) is the most relevant climate parameter for most landslips. Also temperature, e.g. whether the precipitations comes as rain or snow is important and drought.

Debris flows: Extreme rainfall events are the most relevant climate parameter.

Rock falls: Extreme rainfall events (either intense or over a long period) and frost-thaw cycles are relevant climate parameters.

Snow avalanches: Snowfall, frost-thaw cycles and temperature are the most relevant climate parameters.

Impacts
Landslides occur in slopes where the driving force (e.g. gravity) exceeds the resisting force (e.g. friction). Parameters such as geometry and soil moisture might vary with time and hence change the probability of a landslide. Climate changes with *more precipitation* or more *intense precipitation* threatens to enhance soil moisture. Increased water flow in rivers may change the geometry of a slope by erosion. Triggering of a landslide due to erosion at the toe of the slope is a common fact. This might increase the probability of a landslide also in spots that earlier has been considered safe.

Debris flows are triggered *by intense precipitation or snowmelt* in steep slopes where the surface runoff gets concentrated enough to carry soil materials or rocks.

Rock falls refers to rocks falling or sliding freely from a cliff. A rock fall is generally a result of a slow process of weathering and/or *temperature zero-crossings*. Often the fall is triggered by *heavy precipitation*.

Avalanches are to be expected in slopes with *deep and loose snow* where the bottom of the snowpack often is layered by temperature *zero-crossings*.

Rate of change of the climate change impacts
The link between increased precipitation and landslips are recognized but not known. Without detailed site specific surveys it's today not possible to assess how a changed climate will affect the probability of landslips and avalanches. Hence it's also not possible to determine that one counter method is applicable to a certain level of climate change to thereafter be exchanged by a method more suitable to encounter these new circumstances.

This chapter suggests that expected climate change instead is defined as a change occurring in four levels:

- Level 1 – no climate change has occurred
- Level 2 – changes are observed within the relevant climate parameter
- Level 3 – changes in climate has caused minor problems
- Level 4 – changes in climate has caused an event/hazard

This method requires that the slope is stable in the present climate.

Level 1 concerns the current situation. During this phase the road owners are suggested to use measures that involve normal maintenance and mapping.

Level 2 concerns a situation where a change of the relevant climate parameter is observed. This might for instance include a trend of increased precipitation. It might be subjective to determine whether a change has occurred or not and this phase might often be soft transition into Level 3. During this phase the road owners are suggested to rebuild systems to prevent hazards and implement strategies.

Level 3 is reached when problems has been seen due to change of climate. This might for instance be when signs of stability problems are observed. The road owners now need to take practical precautions on the site.

Level 4 involves a post-treatment how to handle a situation after a hazard has occurred.

3.2.3 Step 2: Resilience of the asset in current situation

To meet coming climate changes it's important to first investigate the resilience of the asset in the current situation and being aware of possible spare capacities will ensure a more efficient preparation for a future situation, e.g. is the construction up to today's standards, how does the relevant climate factors influence the asset etc.

The resilience of the asset is site-specific and therefore this step has to be performed by the road owner. It's desirable that this step is following a general mapping of areas with conditions of inclination and geology that make them prone to landslips and avalanches. As previously stated, precipitation in combination with temperature are the most important causes of hazards related to landslips and avalanches. Suggested below are different approaches to determine the resilience on a more detailed scale:

Factor of safety. A landslide will occur when the driving force (gravity) exceed the resisting force (friction). The factor of safety (F) is calculated as the shear resistance divided by the shear force and hence if F<1 a landslide will occur. The greater F is the safer the slope is and this might be a useful indicator of the spare capacity of a slope.

Water saturation. If the slope is water saturated or if the water pressure even is artesian a landslide is more likely to occur. A sufficient drainage system will give the slope a spare capacity to resist heavy precipitation.

Modeling of surface runoff. A debris flow is likely to occur if big amounts of water are likely to run-off through the same gorge or slope. Hydrological modeling can give answers to where the water will flow and which amount of rainfall that can be handled before the flow gets big enough to trigger a debris flow.

Modeling of terrain. Modeling of the slope and areas below might show how far masses from an occurred landslide, debris flow, rock fall or avalanche might reach. For the two latter it might also give answers to which size of rocks or amounts of snow needed to reach a road at threat.

3.2.4 Step 3: Resilience of the asset in possible future situations

As for step 2, this step has to be performed by the road owner at specific sites and often this step will be answered already in step 2 if scenarios for climate change have been analysed.

It's important that road owners keep track of eventual threshold levels as suggested in step 2 and then know about when to react regarding their spare capacity.

3.2.5 Step 4: Identification of applicable / appropriate adaptation measures

Table 21 presents a list of adaptation measures and their effects on landslips and avalanches.

Note: the measures were selected in the database by applying the filter '03 Landslips and avalanches' and respective 'category of measure'.

Table 21: Adaptation measures

Measure	03-1 External slides affecting the road	03-2 Slides of the road embankment	03-3 Debris flow	03-4 Rock fall	03-5 Snow avalanches
Legislation , regulations					
Implement a system of geotechnical risk management	X		X	X	
Maintenance and replacement					
Artificial triggering (active control) of avalanches					X
Inspect and clean watercourses regularly	X	X	X		
Perform controlled explosions or other measures to remove loose rocks				X	
Rebuild stretches of the road on safe ground	X	X	X	X	X
Monitoring					
Continuously measure the pore pressure in slopes	X	X			
Perform regular laser monitoring to detect movement of rocks				X	
Use sensitive seismo-graphs to detect debris flows that have already started moving			X		
Planning					
Apply Rockfall Hazard Rating System (RHRS) on the slope				X	
Carrying out risk assessment of identified areas	X	X	X	X	X
Develop plans and routines of securing areas prone to landslips or avalanches	X	X	X	X	X
Make strategies for temporary rerouting	X	X	X	X	X
Mapping areas prone to landslips or avalanches	X	X	X	X	X
Mapping sites of occurred landslips or avalanches	X	X	X	X	X
Research					
Assess the risk of landslides based on pore pressure	X	X			
Study the relationship between intense rainfalls and landslides to create threshold levels of when to a landslip	X	X	X	X	
Study the relationship between rock fall and precipitation				X	
Study the relationship between intense rainfalls and debris flows to create threshold levels of when to expect a failure			X		

Measure	03-1 External slides affecting the road	03-2 Slides of the road embankment	03-3 Debris flow	03-4 Rock fall	03-5 Snow avalanches
Resilient construction					
Resize drainage systems to meet threats	X	X	X	X	
Avoid deforestation on slopes	X		X	X	X
Robust construction					
Build channels or deflecting walls to direct the flow			X		
Construct a ditch at the toe of the slope			X	X	
Cover slope with rock blanket, vegetation or a retaining structure	X	X			
Cutting back the slope to a shallower angle	X	X			
Ensure efficient drainage systems	X	X	X	X	
Install active protection systems to prevent rock detachments				X	
Install barriers and/or dams to catch material			X	X	X
Install erosion barriers soon after a wildfire	X	X			
Install passive protection systems to protect infrastructure below the slope				X	
Install protective walls/barriers to divert and/or channelizing masses			X		X
Install sheds or walls to protect roads			X	X	X
Install supporting structures in the starting zone					X
Stabilize the surrounding area	X	X			
Support the slope with a retaining structure	X	X			
Traffic management					
Lane closure	X	X	X	X	X
Rerouting	X	X	X	X	X
Determine whether vehicles have been hit	X		X	X	X

3.2.6 Step 5: Establishing a policy

Table 22 to Table 26 present the measures for landslips and avalanches in the policy matrix.

The matrices were produced from the database by selecting the measures first and then applying the macro CTRL+y.

Table 22: Policy matrix for External slides affecting the road

STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
			In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Avoid deforestation on slopes / Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to landslides / Implement a system of geotechnical risk management / Implement a system of geotechnical risk management / Install erosion barriers soon after the wildfire / Mapping areas prone to landslides / Mapping sites of occurred landslides			**EXTREME EVENT MANAGEMENT:** Stabilize the surrounding area			
Robust construction		**PREVENTION:** Cover slope with rock blanket / Cover slope with vegetation / Cutting back the slope to a shallower angle / Spread mulch over the soil to protect it / Support the slope with a retaining structure					
Legislation, regulations							
Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Rebuild stretches of the road on safe ground / Resize drainage systems to meet threats					
Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT:** Inspect and clean watercourses regularly				
Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Carriageway cross-over / Lane closure / Make strategies for temporary rerouting					
Capacity building							
Monitoring	**MONITORING AND PREDICTION:** Continuously measure the pore pressure in the slope						
Research	**RESEARCH:** Assess the risk of landslides based on pore pressure / Study the relationship between intense rainfalls and landslides to create threshold levels of when to expect landslides						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

Table 23: Policy matrix for Slides of the road embankment

	STAGES	PRO-ACTION	PREVENTION	PREPARATION: In preparation of an extreme event	PREPARATION: Just before an extreme event	RESPONSE: During an extreme event	RESPONSE: Just after an extreme event	RECOVERY: After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	PRO-ACTIVE ATTITUDE: Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to landslides / Ensure efficient drainage systems / Implement a system of geotechnical risk management / Install erosion barriers soon after the wildfire / Mapping areas prone to landslides / Mapping sites of occurred landslides			EXTREME EVENT MANAGEMENT: Reroute the traffic / Stabilize the surrounding area			
	Robust construction		PREVENTION: Cover slope with rock blanket / Cover slope with vegetation / Cutting back the slope to a shallower angle / Support the slope with a retaining structure					
	Legislation , regulations							
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Rebuild stretches of the road on safe ground / Resize drainage systems to meet threats					
	Maintenance and management			PREVENTIVE MAINTENANCE AND REPLACEMENT: Inspect and clean watercourses regularly				
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Lane closure / Make strategies for temporary rerouting					
	Capacity building							
	Monitoring	MONITORING AND PREDICTION: Continuously measure the pore pressure in the slope						
	Research	RESEARCH: Assess the risk of landslides based on pore pressure / Study the relationship between intense rainfalls and landslides to create threshold levels of when to expect landslides						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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Table 24: Policy matrix for Debris flows

	STAGES	PRO-ACTION	PREVENTION	PREPARATION: In preparation of an extreme event	PREPARATION: Just before an extreme event	RESPONSE: During an extreme event	RESPONSE: Just after an extreme event	RECOVERY: After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	PRO-ACTIVE ATTITUDE: Avoid deforestation on slopes / Build channels or deflection walls to direct the flow / Carrying out risk assessment of identified areas / Construct a catch ditch at the toe of the slope / Develop plans and routines for the priority of securing areas prone to debris flows / Ensure efficient drainage systems / Implement a system of geotechnical risk management / Install barriers to catch material in debris flows / Install dams to arrest and store debris / Install protective walls/barriers to divert masses / Install sheds or walls to protect roads / Mapping areas prone to debris flows / Mapping sites of occurred debris flows / Use sensitive seismographs to detect debris flows that have already started moving			EXTREME EVENT MANAGEMENT: Reroute the traffic			
	Robust construction							
	Legislation , regulations							
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Rebuild stretches of the road on safe ground / Resize drainage systems to meet threats					
	Maintenance and management			PREVENTIVE MAINTENANCE AND REPLACEMENT: Inspect and clean watercourses regularly				
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Lane closure / Make strategies for temporary rerouting / Make strategies for temporary rerouting					
	Capacity building							
	Monitoring							
	Research	RESEARCH: Study the relationship between intense rainfalls and debris flows to create threshold levels of when to expect a failure						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

Table 25: Policy matrix for Rock fall

STAGES		PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
OBJECTIVES		*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE: Apply Rockfall Hazard Rating System (RHRS) on the slope / Carrying out risk assessment of identified areas / Construct a catch ditch at the toe of the slope / Develop plans and routines for the priority of securing areas prone to rock falls / Ensure efficient drainage systems / Implement a system of geotechnical risk management / Install passive protection systems to protect infrastructure below the slope / Install sheds or walls to protect roads / Mapping areas prone to rock falls / Mapping sites of occurred rock falls**			**EXTREME EVENT MANAGEMENT: Reroute the traffic**			
	Robust construction		**PREVENTION: Install active protection systems to prevent rock detachments.**					
	Legislation , regulations							
	Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION: Rebuild stretches of the road on safe ground**					
	Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT: Perform controlled explosions or other measures to remove loose rocks**				
	Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT: Lane closure / Make strategies for temporary rerouting**					
	Capacity building							
	Monitoring	**MONITORING AND PREDICTION: Perform regular laser monitoring to detect movement of rocks**						
	Research	**RESEARCH: Study the relatiosnship between rock fall and precipitation**						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

Table 26: Policy matrix for Snow avalanches

STAGES		PRO-ACTION	PREVENTION	PREPARATION: In preparation of an extreme event	PREPARATION: Just before an extreme event	RESPONSE: During an extreme event	RESPONSE: Just after an extreme event	RECOVERY: After an extreme event
OBJECTIVES		*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	PRO-ACTIVE ATTITUDE: Artificial triggering (active control) of avalanches / Avoid deforestation on slopes / Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to avalanches / Install dams to arrest and store snow / Install sheds or walls to protect roads / Install supporting structures in the starting zone / Mapping areas prone to avalanches / Mapping sites of occurred avalanches			EXTREME EVENT MANAGEMENT: Reroute the traffic			
	Robust construction							
	Legislation, regulations							
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Rebuild stretches of the road on safe ground					
	Maintenance and management							
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Lane closure / Make strategies for temporary rerouting					
	Capacity building							
	Monitoring							
	Research							

‘Do minimum’ and ‘Develop contingency plans’ strategy
‘Future-proof designs’, ‘Retrofit solutions’ and ‘Update operating procedures’ strategies
‘Monitoring’ strategy
‘Research’ strategy

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3.2.7 Step 6: Assessment of consequence criteria for measures

Table 57 to Table 61 in Annex C present the assessment of the consequences of implementing the measures for landslides, debris flows, rock falls and avalanches respectively.

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

3.2.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. 'Do minimum' strategy: principally the 'Pro-active attitude' in Table 22 to Table 26. The 'Pro-active attitude' policy implies the preparation of contingency plans.
2. 'Future-proof designs' and 'Update operating procedures' strategies: a combination of Upgrading, Prevention and Monitoring and prediction policies in Table 22 to Table 26. The upgrading policy implies resizing drainage systems. The prevention policy implies changing the inclination of a slope or using active protection.
3. 'Monitoring' strategy: this strategy will build up a knowledge base of deterioration models and the impacts of site factors, allowing better informed decisions for maintenance and upgrading.
4. 'Research' strategy: this strategy aims at improving the measures implemented in the first two strategies.

The decision to adopt a strategy or shift from one strategy to another is very site-specific and can be difficult. A help to judge when to use another set of counter measures is to use the levels of climate impact as suggested in chapter 3.2.2. By sorting the measures under each level and being updated on the current level of climate impact, the road owner can take appropriate measures. The division of measures into each level might be site-specific, as well as the degree of measure and therefore has to be implemented by the road owner. The level 2 measures could be seen as complementary measures to level 1. Some of the measures in level 3 may also apply to level 4, when a landslide has occurred. An example for slides of road embankment is given in Table 27.

Table 27: Example of measures for each level of climate impact for Slides of road embankment

Measure	**Level 1(no climate change)**	**Level 2 (observed climate change)**	**Level 3 (climate change have caused signs of instability)**	**Level 4 (climate change has caused a landslide)**
Assess the risk of landslides based on pore pressure	X			
Carrying out risk assessment of identified areas	X			
Continuously measure the pore pressure in the slope	X			
Cover slope with rock blanket			X	
Cover slope with vegetation			X	
Cutting back the slope to a shallower angle			X	
Develop plans and routines for the priority of securing areas prone to landslides	X			
Implement a system of geotechnical risk management	X			
Inspect and clean watercourses regularly	X			
Install erosion barriers soon after the wildfire			X	
Install protective walls/barriers to divert masses		X		
Make strategies for temporary rerouting	X			
Mapping areas prone to landslides	X			
Mapping sites of occurred landslides	X			
Rebuild stretches of the road on safe ground			X	
Reroute the traffic				X
Resize drainage systems to meet threats		X		
Stabilize the surrounding area				X
Study the relationship between intense rainfalls and landslides to create threshold levels of when to expect landslides		X		
Support the slope with a retaining structure			X	

3.2.9 Step 8: Stakeholders to be involved

The main stakeholder is the NRA, but also local municipalities and landowners have to be involved for measures that affect areas outside the road. Funding agencies need to be aware of the additional cost for adaptation, and the impacts of the 'Do minimum' strategy.

3.2.10 Step 9: Existing knowledge gaps

The link between landslips and increased precipitation is strong but there remains an uncertainty of how a change of climate will change the frequency of landslips. There are uncertainties regarding how much of the precipitation that will add to an increase of the ground water level and whether it will lead to loss of negative pore pressures that act stabilising on certain slopes. There are also uncertainties on what increase in precipitation that will lead to water flows critical for erosion. Studies performed in recent years, for instance by Crozier [12] and Meynard et al [13], indicate that this quandary is still present and further research has to be done.

3.2.11 Step 10: Time to market of upcoming techniques

New techniques might involve new materials for slope stabilization and active rock fall preventions as well as technical systems for monitoring (possibly TRL 6) .

Different systems of monitoring slopes and cliffs has been developed and tested. Ground-based hyperspectral imager, ground based interferometric radar and digital video cameras have all been tested with good results [14]. Some systems are already in use while others need further development. This is also much dependent on the type of slopes. While some systems are in use others have an expected time to market is within 5-10 years.

Terrestrial lasers scanning (TLS) is already a widely spread technique in many countries and it provides information about topology that is very useful when predicting spots prone to landslips and avalanches. Current fields of use is monitoring, modelling inclination, and hydrographical information but other usages are likely to arise in a near future.

3.3 Uplift of tunnels or light weight construction materials by increasing water levels

3.3.1 Step 0: The road owner's needs

Relevance to the road owner
In most parts of Europe precipitation, sea level and wind speeds will increase as a result of climate change, leading to an increase in groundwater levels and a potential loss of road structure integrity:

- Increase of uplift pressures at the bottom of tunnels, deep-lying road stretches, causing structural damage;
- Increase of uplift pressures at the bottom of light weight fills, causing damage to pavement and road embankment.

The damage from the combined changes in precipitation, sea level and wind speeds will cause a decrease in availability due to repair or replacement works, an increase in maintenance cost, and potential loss of confidence of the public in the ability of the road owner to deal with climate change impacts.

Little data have been found on the vulnerability of the EU network and potential magnitude of the damage. The Blue spots vulnerability assessment study for the Netherlands [31] found 116 potentially vulnerable objects or locations on a network length of 2300 km. For most locations (74 out of 116) a specific analysis on a case-to-case basis (based on actual design information of the objects) is necessary. For the other 42 locations it was possible to confirm that these locations are not vulnerable to a possible change of the groundwater table due to climate change. A risk assessment study in the Netherlands [32] revealed that failure of an object by uplift will lead to complete closure of the road for a short or long period. The risk (probability x consequences) of uplift is ranked highest as compared to other precipitation / flood related risks. Twenty of the potentially vulnerable locations were classified as being at great risk.

As an indication of the consequences, the Vlaketunnel in the Netherlands was closed for several weeks in 2011 and had reduced capacity during 5 months, following uplift of part of the entry. The uplift was due to failure of tension elements, not to changing groundwater levels.

Concerns of the NRAs
The PEB members did not identify any specific road owner's problems related to uplift of tunnels or light weight fills by increasing water levels.

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs. The report does not mention concerns related to uplift of tunnels or light weight fills by increasing water levels.

3.3.2 Step 1: Definition of the relevant climate variable from design guidelines

The relevant design parameters are the maximum groundwater pressure or maximum groundwater level during the lifetime of the construction. The groundwater pressure or level are related to external variations of precipitation or river or sea levels through the geohydrological properties of the soil around the structure.

Therefore, relevant climate parameters are one or more of the following:
- Precipitation in the area around the construction.
- Precipitation in the catchment area of rivers near the construction.
- Higher temperatures causing snow melt in the catchment area of rivers near the construction.
- Sea level rise and storm surge by wind near the construction.

Most design guidelines specify a factor of safety against uplift to be applied to groundwater pressures (e.g. Eurocode 7, [28]). Specifications for the determination of the maximum groundwater pressure or level are usually less clearly defined. Guidelines will typically state that 'climate change during the lifetime of the construction should be taken into account' but do not specify climate parameters or climate change scenarios.

Analysis of historical data can reveal relations between precipitation and river and sea levels for calibration of local geohydrological models. The same geohydrological models may be used to estimate the effects of changes of the climate parameters on groundwater level or pressure.

3.3.3 Step 2: Resilience of the asset in current situation

Many constructions have been designed using groundwater levels and pressures that reflect climate conditions prior to the year 2000. Some constructions have passive or active provisions such as drainage systems to warrant that groundwater levels will not exceed the maximum design values.

3.3.4 Step 3: Resilience of the asset in possible future situations

The vulnerability of constructions to climate change will depend on many local factors and needs to be assessed on a case-by-case basis, as in the Blue spots vulnerability assessment study for the Netherlands [31].

The first step in the assessment will consist of estimating future maximum groundwater levels and pressures, using local geohydrological models and projections of changes in the climate parameters. If the future groundwater level at the location of the construction exceeds the present day level the construction is potentially vulnerable. Some constructions are not vulnerable because of their geometrical characteristics, such as distance between the base level of the object and groundwater table. This step requires detailed design information.

The second step will be the assessment of the impacts of the future maximum groundwater levels and pressures on the performance of the construction. Design codes at the time of design of the construction will need to be considered, and the actual capacity of provisions to limit groundwater levels, if present, and the actual capacity of provisions to resist uplift. The past design codes can be obtained by interviewing experts of the NRA.

Maintenance of provisions to limit groundwater levels will become more critical as climate change progresses. Also, inspection and maintenance of provisions to resist uplift such as tension elements will become more critical.

3.3.5 Step 4: Identification of applicable / appropriate adaptation measures

Table 28 presents a list of adaptation measures for uplift of tunnels and deep-lying road stretches, and for uplift of light weight fills.

Note: the measures were selected in the database by applying the filter '04-5 Uplift of tunnels or light weight construction materials by increasing water levels' in column C 'Threat sub category'.

Table 28: Adaptation measures

Nr.	Measure	Tunnels and deep-lying road stretches	Light weight fills
	Legislation, regulations		
413	Revised standards for design of tunnels, tunnel entries, excavations and light weight fills	X	X
	Maintenance and management		
404	Appropriate inspection and maintenance of drainage, pumping and waterproofing systems	X	X
	Monitoring		
408	Monitor ground water table	X	X
	Planning		
403	Apply surcharge to counter uplift as emergency measure	X	X
405	Collect relevant construction data	X	X
409	Develop contingency plans	X	X
	Research		
410	Preventive information	X	X
	Robust construction		
401	Adapt drainage system to control ground water table	X	X
402	Apply surcharge to counter uplift	X	X
406	Install pumping systems to control ground water table	X	X
414	Strengthen tension piles of excavations	X	
	Traffic management		
407	Modal shift	X	X
411	Real time traffic information	X	X
412	Rerouting and guidance	X	X

3.3.6 Step 5: Establishing a policy

Table 29 presents the policy matrix with the measures for Loss of road structure integrity – Uplift of tunnels or light weight construction materials by increasing water levels.

The matrices were produced from the database by selecting the measures first and then applying the macro CTRL+y.

Table 29: Policy matrix for Loss of road structure integrity – Uplift of tunnels or light weight construction materials by increasing water levels

STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
			In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE							
Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE: Collect relevant construction data / Prepare contingency / emergency plans**			**EXTREME EVENT MANAGEMENT: Apply surcharge to counter uplift as emergency measure**			
Robust construction		**PREVENTION: Revised standards for design of excavations and light weight fills**					
Legislation , regulations							
Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION: Adapt drainage system to control ground water table / Apply structural surcharge to counter uplift / Install pumping systems to control ground water table / Strengthen tension**					
Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT: Appropriate inspection and maintenance of drainage, pumping and waterproofing systems**				
Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT: Modal shift / Real time traffic information / Rerouting and guidance**					
Capacity building							
Monitoring	**MONITORING AND PREDICTION: Monitor ground water table**						
Research	**RESEARCH: Preventive information**						

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'Monitoring' strategy
'Research' strategy

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3.3.7 Step 6: Assessment of consequence criteria for measures

Table 62 in Annex C presents the assessment of the consequences of implementing the measures for Loss of road structure integrity – Uplift of tunnels or light weight construction materials by increasing water levels.

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts. E.g. the impact of flooding on availability is more serious than a reduction of driving ability in a heavy rainstorm.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

3.3.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. ‘Do minimum’ strategy: a combination of the ‘Preventive maintenance and management’ and ‘Traffic management ‘policies of Table 29.
   The ‘Preventive maintenance and management’ policy implies that provisions for controlling the groundwater level and resisting uplift are inspected and maintained regularly. The interval of time between maintenance actions may need to be decreased as climate change progresses. The ‘Traffic management’ policy implies imposing access restrictions after failure of a road or tunnel section.
   The additional cost of this strategy will be minimal, but the impacts of an uplift event on availability of the network will be very severe.
2. ‘Future-proof designs’ strategy: a combination of ‘Upgrade, retrofit and new construction’ and ‘Prevention’ policies of Table 29.
   The ‘Upgrade, retrofit and new construction’ policy implies installation of retrofit provisions to control groundwater levels or resist uplift. The ‘Prevention’ policy implies changing specifications of design codes for new construction and procedures for inspection and preventive maintenance.
   This strategy strongly reduced the probability of an uplift event. There will be a cost increase for installation of retrofit provisions and monitoring systems.
3. ‘Update operating procedures’ strategy: a combination of ‘Pro-active attitude’, ‘Monitoring and prediction’ and ‘Extreme event management’ policies of Table 29.
   The ‘Pro-active attitude’ policy implies the preparation of contingency plans and the collection of relevant construction data. The ‘Monitoring and prediction strategy’ will provide data for real-time analysis and prediction of the probability of an event, allowing emergency measures to be taken.
   This strategy focusses on preventing structural damage by installing temporary measures during periods of high groundwater levels. There will be a cost increase for installation of monitoring systems and emergency measures. The impacts of an event on availability of the network are severe but limited in time.
4. ‘Monitoring’ strategy: this strategy will build up a knowledge base of deterioration models and the impacts of site factors, allowing better informed decisions for maintenance and upgrading. The monitoring may also include the socio-economic impacts of implementing or not implementing adaptation measures. This strategy thus serves the decision making between strategies, and the selection of measures in a strategy.
5. ‘Research’ strategy: this strategy aims at improving the measures implemented in the ‘Future proof designs’ and ‘Update operating procedures’ with respect to cost-

effectiveness and network operation. The research may include non-destructive monitoring methods, early warning systems and socio-economic models.

At present, most NRAs adopt the ‘Do minimum’ strategy. Some NRAs have started adapting their design codes as part of the ‘Future-proof designs’ strategy, and collecting data for vulnerability assessment as part of the ‘Update operating procedures’ strategy.

The decision to adopt a strategy or shift from one strategy to another can be based on the following considerations:

- The Monitoring strategy is a no-regret option that facilitates further decision making.
- The impact of higher groundwater levels or pressures on constructions will depend on site specific factors and uncertainty in climate change projections. All decisions should therefore be based on impact studies considering all these factors.
- The remaining service life of most constructions will be substantial, in the order of 30 – 50 years. Cost-benefit studies will help decide between the ‘Do minimum’ strategy, a change to the ‘Future-proof designs’ strategy (applying retrofit provisions), and a change to the ‘Update operating procedures’ strategy.
- For new constructions, cost-benefit studies can support the decision to change to the ‘Future-proof designs’ strategy. Cost-benefit studies need to consider uncertainty in climate change explicitly.
- Cost-benefit studies for specific innovative measures can be initiated as part of the ‘Research’ strategy.

3.3.9 Step 8: Stakeholders to be involved

The main stakeholder is the NRA. Funding agencies need to be aware of the additional cost for adaptation, and the impacts of the ‘Do minimum’ strategy.

3.3.10 Step 9: Existing knowledge gaps

Climate variables

The relevant climate variables and the required temporal and spatial resolution are given below, for uplift of tunnels or light weight construction materials by increasing groundwater levels.

Table 30: Climate variables for uplift of tunnels or light weight construction materials by increasing water levels

Climate variable	Unit	Temporal resolution	Spatial resolution
Precipitation in the area around the construction.	mm/season, mm/year	season – year	10 km
	mm/days	several days – week	10 km
Precipitation in the catchment area of rivers near the construction.	mm/season, mm/year	season – year	100 km
	mm/days	several days – week	100 km
Higher temperatures causing snow melt in the catchment area of rivers near the construction.	˚C and number of (consecutive) days	days-weeks	100 km
Sea level rise near the construction.	cm	days	100 km
Extreme wind speed, wind direction (-> storm surge) at sea near the construction	m/s	hours – days	10 km

Projections for these climate variables need to be available at the correct temporal and spatial resolution.

Upcoming measures
Measures in the Research category of the database are:

- Preventive information: early warning, monitoring and prediction systems for construction integrity.

Various techniques exist for monitoring; the integration of weather prediction, monitoring data, geohydrological and prediction models is an on-going development.

Data to be collected in order to assess the resilience of the asset
The data that need to be collected in order to understand the current capability of the asset and predict the future capability are given below.

- Construction records: design groundwater levels or pressure, applicable design codes, safety factors, capacity of provisions for controlling groundwater level and resisting uplift, as-built construction drawings
- Inspection and maintenance records: deterioration of provisions for controlling groundwater level and resisting uplift
- Monitoring records: groundwater levels or pressures around the construction in relation to climate parameters
- Records of climate variables

3.3.11 Step 10: Time to market of upcoming techniques

The technology readiness level (TRL) of the measures is estimated as:

- Preventive information : early warning, monitoring and prediction systems for construction integrity – TRL 6: prototype demonstrated in relevant environment.

The FEHRL Resilient Road roadmap [3] estimates the following times to market:

- Preventive information : early warning, monitoring and prediction systems for construction integrity – R&D 5 years, demonstration 5 years; regulatory framework 3 years; time to market 2012-2025 (13 years).

3.4 Erosion of road embankments and foundations

3.4.1 Step 0: The road owner's needs

As a result of climate change, precipitation, sea levels and storm frequency will change all over Europe and increasing the erosion along shores, rivers and slopes. Examples of impacts to be expected are:

- Erosion by overloaded hydraulic systems crossing the road due to extreme rainfall events.
- Erosion of road bases due to sea level rise and/ or extreme wind speed.
- Bridge scour due to sea level rise and/ or extreme wind speed.

This chapter deals with damage due to hazards identified above. The hazards are also commonly referred to as "erosion".

All types of erosion of road embankments and foundations may have a considerably negative impact on both the specific site and on the extended road network with predominantly traffic hindrances as possible risk.

Concerns of the NRAs

The PEB members identified the following specific road owner's problems related to erosion in a changed climate:

- What is the capacity of the erosion protection in comparison with current flood levels and/or rain intensity? → chapter 3.4.3
- When should a certain counter measure be applied? → chapter 3.4.6
- Does current design and construction need to be changed to handle both flooding and periods of drought followed by intense precipitation? → chapters 3.4.3 and 3.4.4

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs. Five out of eleven NRAs consider increased flow rates in rivers to be a risk while four NRAs considers sea level rise to be a risk. Norway and France calls for better predictions and guidelines to handle sea level rise as well as better design of wave erosion protection. The latter foresee upcoming problems with low lying road sections, ferries and sub-sea tunnel entrances. Problems due to stronger winds or storms are generally not considered as very severe: one to two NRAs rate this as a risk.

3.4.2 Step 1: Definition of the relevant climate variable from design guidelines

Erosion by overloaded hydraulic systems crossing the road: Extreme rainfall events (either intense or over a long period) are the most relevant climate parameters.

Erosion of road bases: Extreme rainfall events (either intense or over a long period) and sea level rise are the most relevant climate parameters.

Bridge scour: Extreme rainfall events (either intense or over a long period) and sea level rise are the most relevant climate parameters. Extreme wind speed, storm surge may also lead to temporary raised sea levels, causing damages.

Impacts

Erosion by overloaded hydraulic systems crossing the road may occur when more water than the system is designed for are running through culverts. Climate changes of *more precipitation* or more *intense precipitation* threatens to give run-off that exceed current standards and results in erosion at the entrance and/or exit of the culverts. Also snowmelt might cause this type of erosion. For the impacts of climate change on capacity of culverts, see also chapter 2.1.

Erosion of road bases it threatening roads that runs close to open water surfaces, generally the sea, and is thus affected by *sea level rise*. This type of erosion might also be caused by extensive flow in ditches and be caused by water flowing over the road embankment.

Bridge scour refers to the removal of sediments and is caused by flowing water or the secondary vortexes formed near the bridge pier or abutment. Climate changes of *more precipitation* or more *intense precipitation* threatens to increase the flow and thus cause bridge scour.

Rate of change of the climate change impacts
To evaluate the risk of erosion by overloaded hydraulic systems or bridge scour a hydraulic model has to be conducted, identifying parameters such as induced flow from a certain amount of precipitation in the catchment area, critical shear stress and flooded areas for a critical flow. A model to evaluate impacts of climate change on bridge scour is proposed by Khelifa et al (2013) using the free PC software HYRISK [15]. Because of the complexity the evaluation has to be site specific and performed by the NRA.

It's easier to predict flooding, and thereby erosion, caused by sea level rise. Recent research imposes that the sea around Europe will rise with up to 1 meter by 2100 (compared to 1990) [16]. Low-lying road sections have to be identified and counter measures performed accordingly.

3.4.3 Step 2: Resilience of the asset in current situation

To meet coming climate changes it's important to first investigate the resilience in the current situation. Ensuring a sufficient system and being aware of possible spare capacities will ensure a more efficient preparation for a future situation.

The resilience of the asset is site-specific and therefore this step has to be performed by the road owner. It's desirable that this step is following a general mapping of areas with conditions as altitude, soil properties and watercourses that make them prone to erosion. As previously stated, precipitation and sea level rise are the most important causes of hazards related to erosion. Suggested below are different approaches to determine the resilience on a more detailed scale:

Hydrological and hydraulic modeling. Erosion due to overloaded culverts might happen after extensive rainfall (or snowmelt) in the catchment area. Hydrological modeling will give answers to where the water will flow and the response time after precipitation upstream while hydraulic modeling give parameters such as critical shear stress and predicted water level for a certain amount of precipitation. This will reveal eventual resilience in the system.

Modeling of terrain. Modeling of the road base level will reveal sections at risk at sea level rise. Local calculations of sea level rise and eventual land rise will provide an estimation of when measures has to be taken.

Estimating the risk of scour. The risk of scour can be estimated by different criteria. An example of method is proposed by Bundaberg regional council [17] where the risk of scour is rated from parameters such as flood velocity and foundation conditions.

3.4.4 Step 3: Resilience of the asset in possible future situations

As for step 2, this step has to be performed by the road owner at specific sites and often this step has been answered already in step 2, if scenarios for climate change has been analysed.

It's important that road owners keep track of eventual threshold levels as suggested in step 2, e.g critical shear stress, flood velocity, critical sea level etc, and then know about when to react regarding their spare capacity.

3.4.5 Step 4: Identification of applicable / appropriate adaptation measures

Table 31 presents a list of adaptation measures and their effects on erosion of road embankments and foundations.

Note: the measures were selected in the database by applying the filter '02 Erosion of road embankments and foundations' and respective 'category of measure'.

Table 31: Adaptation measures

Nr.	Measure	Erosion by overloaded hydraulic systems crossing the road	Erosion of road bases	Bridge scour
Capacity building				
174	Prepare and educate road users for flooding	X	X	X
175	Prepare and educate staff for flooding	X	X	X
Legislation, regulations				
161	Establish a guideline for standardized inspection of culverts	X		
187	Revised standards for design of culverts	X		
188	Revised standards for road design, avoiding buildup of water level differences	X		
Maintenance and management				
154	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall.	X		X
162	Inspect and clean watercourses regularly	X	X	
190	Take measures to reduce downstream sedimentation and clean debris and sediment from the outlet ditch	X		
208	Rebuild stretches of the road on safe ground		X	
218	Inspect bridge foundations and surroundings (over and under water) regularly			X

Nr.	Measure	Erosion by overloaded hydraulic systems crossing the road	Erosion of road bases	Bridge scour
Planning				
149	Avoid urbanisation and watersheds diversions in vulnerable areas	X		X
153	Carrying out risk assessment of identified areas	X		
159	Develop plans and routines for the priority of securing areas prone to be affected by sea level rise	X	X	
165	Keep in-house GIS up to date	X	X	X
166	Keep records of events and locations of overloaded hydraulic systems/flooding	X	X	X
169	Make strategies for temporary rerouting	X	X	X
207	Map areas prone to flooding (‘blue spot analysis’)	X	X	X
Research				
211	Reviewing design storm return periods in the light of new weather information	X	X	X
Resilient construction				
148	Avoid deforestation in the catchment area	X		X
150	Build dams, reservoirs and retaining ponds to buffer the water	X		X
158	Cover slope with vegetation	X		X
172	Organize weirs/overflow towards storage facilities	X		X
182	Replace the culvert with a small bridge	X		
185	Resize drainage systems to meet threats	X		X
195	Construct detention storages	X		
213	Check dams - installing sills or drop structures	X		X
Robust construction				
151	Build flood walls to protect road from flooding		X	
156 157	Cover road embankment with geotextile, rock blanket or vegetation	X	X	X
160	Dredge the channel to increase depth and/or width	X		
173	Pave the inlet or the outlet of the culvert	X		
201	Flatten the road embankment	X		
216	Extend the footing to support the slope	X		

Nr.	Measure	Erosion by overloaded hydraulic systems crossing the road	Erosion of road bases	Bridge scour
217	Increase span/ relief bridge			X
219	Install a bulkhead to support the slope and protect it from erosion	X	X	X
220	Install debris basins to collect debris			X
221	Install flexible revetment as artificial armouring			X
222	Install flow deflecting plates do deflect flow			X
223	Install jetties to support the slope or protect bank from erosion		X	X
224	Install vanes upstream to reduce flow			X
228	Protect foundation and surroundings with gabions/ reno mattresses or concrete pavement			X
229	Protect foundations and surroundings with guide banks (spurs/dyke)			X
244	Underpinning to strengthening the columns			X
Traffic management				
38 42 43 55 59 62 67 70 71 75 76 80	Access restriction + Carriageway cross-over + Lane closure + Modal shift + Real time traffic information + Rerouting and guidance + Reroute the traffic + Speed limits	X		
176	Prepare traffic management plans	X		

3.4.6 Step 5: Establishing a policy

Table 32 to Table 34 present the measures for Erosion of road embankments and foundations, Erosion of road bases and Bridge scour in the policy matrix.

The matrices were produced from the database by selecting the measures first and then applying the macro CTRL+y.

Table 32: Policy matrix for Erosion of road embankments and foundations

STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
			In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
Planning for CCI&EWE	PRO-ACTIVE ATTITUDE: Avoid deforestation in the catchment area / Avoid urbanisation and watersheds diversions in vulnerable areas / Build dams, reservoirs and retaining ponds to buffer the water / Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Develop plans and routines for the priority of securing areas prone to overloaded hydraulic systems / Dredge to increase depths and/or straighten the stream / Keeping in-house GIS up to date / Keeping records of events and locations of overloaded hydraulic systems / Organize weirs/overflow towards storage facilities / Pave the inlet and the outlet of the culvert / Wetland restoration as part of a strategy of multiply lines of flood defences			EXTREME EVENT MANAGEMENT: Modal shift / Reroute the traffic			
Robust construction		PREVENTION: Cover road embankment with geotextile / Cover slope with rock blanket / Cover slope with vegetation / Protect entrance embankment with rock blanket / Protect entrance against floating debris / Rebuild stretches of the road on safe ground / Revised standards for design of culverts / Revised standards for road design, avoiding buildup of water level differences / Take measures to reduce downstream sedimentation and clean debris and sediment from the outlet ditch afterwards.					
Legislation, regulations							
Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Replace the culvert with a small bridge / Resize drainage systems to meet threats					
Maintenance and management			PREVENTIVE MAINTENANCE AND REPLACEMENT: Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall / Clear natural blockages such as shrubs and weeds / Establish a guideline for standardized inspection of culverts / Inspect and clean watercourses regularly / Inspect blue spots areas adjacent to heavy rainfalls				
Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Carriageway cross-over / Install sign posts warning for flooding in threatened areas / Lane closure / Make strategies for temporary rerouting / Prepare Traffic Management Plans / Real time traffic information / Real time weather and traffic forecast / Rerouting and guidance / Speed limits					
Capacity building	CAPACITY BUILDING: Prepare and educate road users for flooding / Prepare and educate staff for flooding						
Monitoring	MONITORING AND PREDICTION: Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Reviewing design storm return periods in the light of new weather information						
Research							

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

Table 33: Policy matrix for Erosion of road bases

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Build flood walls to protect the road from flooding / Carrying out risk assessment of identified areas / Construct detention storages / Develop plans and routines for the priority of securing areas prone to be affected by sea level rise / Flatten the road embankment / Keeping in-house GIS up to date / Keeping records of flooding events and locations / Mapping areas prone to flooding (Blue spot analysis) / Vegetation along the slope of the road embankment to reduce wave action and stream velocity			**EXTREME EVENT MANAGEMENT:** Reroute the traffic			
	Robust construction		**PREVENTION:** Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall / Cover road embankment with geotextile / Cover slope with rock blanket / Cover slope with vegetation / Cover the road embankment with hard protection to reduce wave action / Install or raise the level of existing protecting wall outside the road					
	Legislation, regulations							
	Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Rebuild stretches of the road on safe ground / Resize drainage systems to meet threats					
	Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT:** Inspect watercourses regularly				
	Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Make strategies for temporary rerouting					
	Capacity building							
	Monitoring							
	Research	**RESEARCH:** Reviewing design storm return periods in the light of new weather information						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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Table 34: Policy matrix for Bridge scour

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
	Planning for CCI&EWE				EXTREME EVENT MANAGEMENT: Reroute the traffic			
	Robust construction							
CATEGORY OF ADAPTATION MEASURE	Legislation, regulations	PRO-ACTIVE ATTITUDE: Check dams - installing sills or drop structures / Extend the footing to support the slope or protect it from erosion / Install debris basins to collect debris / Install vanes upstreams to reduce flow / Keeping in-house GIS up to date	PREVENTION: Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall / Dredge the channel to increase the width and/or depth / Install a bulkhead to support the slope and protect it from erosion / Install flexible revetment as artifical armoring / Install flow deflecting plates to deflect flow / Install jetties to support the slope or protect bank from erosion / Plant vegetation to prevent bank erosion / Protect foundation and surroundings with gabions/ reno mattress / Protect foundations and surroundings with bituminous concrete pavement / Protect foundations and surroundings with fabric bags filled with concrete and stacked to produce a protective layer / Protect foundations and surroundings with guide banks (spurs/dyke) / Protect foundations and surroundings with rock or gravel blankets / Protect foundations or surroundings with artificial riprap or tetrapods /toskanes / Protect foundations or surroundings with cable-tied blocks / Protect foundations or surroundings with concrete grouted riprap / Protect foundations or surroundings with precast concrete blocks with retard (timber & sheet piles) / Protect foundations or surroundings with sacrificial piles upstream to reduce velocity / Protect foundations with structures that dissipate energy in the water / Stabilize the slope with soil cement					
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Increase span/relief bridge / Resize drainage systems to meet threats / Underpinning to stengthening the columns					
	Maintenance and management			PREVENTIVE MAINTENANCE AND REPLACEMENT: Inspect bridge foundations and surroundings (over and under water) regularly				
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Make strategies for temporary rerouting / Rerouting and guidance					
	Capacity building							
	Monitoring							
	Research	RESEARCH: Reviewing design storm return periods in the light of new weather information						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

3.4.7 Step 6: Assessment of consequence criteria for measures

Table 63 to Table 65 in Annex C present the assessment of the consequences of implementing the measures for erosion due to overloaded hydraulic systems, erosion on road bases and bridge scour respectively.

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

3.4.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. ‘Do minimum’ strategy: principally the ‘Pro-active attitude’ in Table 32 to Table 34. The ‘Pro-active attitude’ policy implies the preparation of contingency plans.
2. ‘Future-proof designs’ and ‘Update operating procedures’ strategies: a combination of Upgrading, Prevention and Monitoring and prediction policies in Table 32 to Table 34. The upgrading policy implies resizing drainage systems and installing extra scour protection.
3. ‘Monitoring’ strategy: this strategy will build up a knowledge base of deterioration models and the impacts of site factors, allowing better informed decisions for maintenance and upgrading.
4. ‘Research’ strategy: this strategy aims at improving the measures implemented in the first two strategies.

The decision to adopt a strategy or shift from one strategy to another can be based on the following considerations:

- The ‘Do minimum strategy’ keeps costs of today at a minimum but risks to be more expensive in the future.
- For upgrading existing roads cost-benefit studies will help decide between maintaining current culverts and foundations and applying new constructions that are more resilient to more precipitation and run-off. The selection of more resilient constructions will depend on the anticipated development of precipitation over the additional service life, using present climate change projections.
- For new construction of roads, cost-benefit studies can support the decision to change to the ‘Future-proof designs’ strategy. Cost-benefit studies need to consider uncertainty in climate change explicitly.
- The ‘Monitoring strategy’ is a no-regret option that facilitates further decision making.

3.4.9 Step 8: Stakeholders to be involved

The main stakeholder is the NRA, but also local municipalities and landowners have to be involved for measures that affect areas outside the road. Funding agencies need to be aware of the additional cost for adaptation, and the impacts of the ‘Do minimum’ strategy.

3.4.10 Step 9: Existing knowledge gaps

The process of erosion due to action of currents and waves in different type of soils needs to be further investigated. Cohesive sediments react differently to shear stress, compared to coarser materials and this needs to be described. Further, existing models of erosion and scour has to be develop to a more detailed level. There are uncertainties on what increase in precipitation that will lead to water flows critical for erosion in the different type of soil.

3.4.11 Step 10: Time to market of upcoming techniques

New techniques might involve new materials for erosion controls as well as systems for monitoring. This development occurs constantly in the private sector. Some of the systems have a TRL 7-8, e.g. Vegetation as erosion control.

4 Road deterioration from climate change

4.1 Heat stress on bituminous and semi-rigid pavements

4.1.1 Step 0: The road owner's needs

Relevance to the road owner
All around Europe temperatures will increase as a result of climate change, resulting in pavement deterioration:
- Increased cracking, rutting, embrittlement of bituminous binders, loss of surface texture, migration of liquid bitumen in bituminous and semi-rigid [1]pavements, due to higher summer temperatures;
- Increased thermal expansion of concrete pavements, due to higher summer temperatures;
- Increased cracking of pavements after loss of bearing capacity by spring thaw, due to higher winter and spring temperatures;
- A decrease in utility of (unimproved) roads that rely on frozen ground, due to higher winter and spring temperatures.

Positive impacts from higher winter and spring temperatures are:
- A decrease in costs for de-icing;
- A decrease in low temperature cracking;
- A decrease in frost heave, because of fewer frost-thaw cycles;
- A decrease in damage from studded tyres;
- A decrease in aggregate loss and detachment of pavement layers because of frost.

This chapter deals with damage to bituminous and semi-rigid pavements, due to higher summer temperatures. The impact is also referred to as "heat stress in bituminous and semi-rigid pavements".

The damage from higher summer temperatures will cause a decrease in availability due to maintenance works, a reduction in driver safety because of loss of skidding resistance by liquid bitumen migration and increased aquaplaning in ruts, an increase in maintenance cost, and potential loss of confidence of the public in the ability of the road owner to deal with climate change impacts.

The report of the EU Joint Research Council [1] compares weather and climate induced infrastructure deterioration to deterioration due to traffic loading. Separating the two main factors for pavement degradation (weather conditions and traffic) is rather difficult. Therefore, the faction of national aggregated maintenance costs attributable to weather can't be unequivocally assessed. Considering a 30%-50% contribution from weather conditions to total pavement deterioration for Europe would represent from 8 to 13 billion euros/yr weather-induced costs for Europe. This number represents frost-thaw, precipitation and heat induced damage. In hot climates such as in Australia, temperature-related costs account for 36% of current maintenance costs for roads [4]. This number includes both asphalt and concrete pavements.

[1] Semi-rigid pavements comprise an asphalt layer laid onto a hydraulically bound pavement layer. Semi-rigid pavement construction gained popularity in Europe during the 1970's when, due to an escalation in the oil price, the unit cost of asphalt increased. Since semi-rigid pavements utilise less asphalt than their fully-flexible counterparts, economic efficiency of this type of construction increased.

Concerns of the NRAs
The PEB members identified the following specific road owner's problems related to heat stress in bituminous and semi-rigid pavements:

- How will climate change affect the service life of a specific road? Will there be any dramatic changes due to climate change? → see chapter 0
- How can one limit rutting, cracks etc.? Should one look at design rules? Materials? → see chapter 4.1.5
- Concerning the impacts of higher asphalt temperatures – can one wait until the next planned paving to introduce a better asphalt type? → see chapter 4.1.8

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs. Nine out of eleven NRAs consider higher temperatures a serious risk. Hungary and Spain specifically mention problems related to deformation and durability of flexible pavements. French, Italian and Spanish NRAs feel a need for research on the impact of heat on pavements. The Swedish NRA identifies the need for a socio-economic study concerning what model to use in the future: strengthen the roads, repair them afterwards, or not allow heavy traffic during the winter.

Impacts
A study by TRL for the UK Department of Transport [33] lists the following effects of heat on flexible pavements.

Age hardening (embrittlement) increases the viscosity of the binder and depends on temperature, time and the bitumen film thickness. The hardening process will progress faster with higher pavement temperatures and greater porosity of the asphalt mixture. Excessive age hardening can result in brittle binder with significantly reduced flow capabilities. This hardening produces both negative and positive effects. In thin asphalt pavements, age hardening is not desirable, as it will decrease the ability of the pavement to flex under traffic loads. In addition, premature cracking will result from thermal and traffic induced stresses and strains. Hardening of the base and binder course materials of thick asphalt pavements increases their stiffness modulus and hence improves their load-spreading ability. Higher average temperatures increase the rate of oxidative age hardening and will therefore accelerate the appearance of surface cracks.

Top-down cracking Observations in the UK have shown that the majority of the cracks in fully flexible and flexible composite pavements initiate at the road surface and propagate downwards. Oxidation and the action of UV radiation cause excessive hardening of the asphalt close to the pavement surface and the material to become brittle over time. In this condition, thermal and load-induced stresses can cause crack initiation and propagation. Hotter weather speeds up the oxidation process and makes the material more vulnerable to cracking, while cooler diurnal temperatures generate thermal tensile stresses that can cause crack initiation and propagation.

Cracking initiated at the bottom of the base course (bottom up cracking) The base layer is the main load-spreading layer in a fully flexible pavement, and the stiffness modulus is a measure of its load-spreading ability. The higher the temperature, the lower the stiffness modulus and the greater the risk of fatigue cracking in the asphalt base layer and structural deformation in the subgrade.

Rutting originating in the bituminous layers The resistance to rutting of the asphalt surfacing depends on road temperature as well as the traffic load. At high temperatures, asphalt becomes more susceptible to deformation, and rutting is more likely to occur, particularly on highly trafficked roads and at low traffic speeds. Research has found that the majority of rutting in the asphalt surfacing occurs on a few days of the year, when the temperature of the road surfacing exceeds 45°C. The susceptibility of an asphalt's deformation resistance to changes in temperature depends on the type of mixture. Rutting resistance can be increased by using a more angular aggregate and an aggregate grading that provides a good aggregate skeleton and/or a binder with better high-temperature properties and good mixture design. Specific additives exist to increase the rutting resistance. Generally, they are incorporated directly into the mixer of asphalt plant.

Loss of surface texture Low viscosity binders will allow the penetration of surface chippings on hot days, causing a loss of surface texture and reduced skid resistance.

Fatting up (migration of liquid bitumen) Migration of low viscosity binder to ruts will cause a reduction of skid resistance. Fatting up can be limited by using of polymer modified bitumen.

4.1.2 Step 1: Definition of the relevant climate variable from design guidelines

Traffic loading and temperature are the two most important causes of pavement deterioration. This chapter gives models commonly used for pavement design with respect to the different deterioration mechanisms. Most models allow the separation of effects of traffic loading and temperature.

Table 35 lists the design models and climate parameters for the heat related deterioration mechanisms in flexible pavements. The increase of the annual mean temperature can modify the pavement structure design. For the bituminous structure, some models used the notion of equivalent temperature. This equivalent temperature is affected by increased of mean air temperature. The modulus of asphalt concrete decreases and the fatigue resistance increases. Also, Poisson's ratio can be affected.

Table 35: Design models and climate parameters

Deterioration mechanism	Design model	Climate parameter
Age hardening (embrittlement)	No reliable model available [5]	Annual heat sum > 25°C (hours x Kelvin) [8]
Top-down cracking	ME-PDG [6], [7]	Records of mean monthly air temperature / continuous temperature records
Cracking initiated at the bottom of the base course	ME-PDG [6], [7]	
Rutting originating in the bituminous layers	ME-PDG [6], [7]	
Loss of surface texture	No reliable model available	Annual heat sum > 25°C (hours x Kelvin) [8]
Fatting (migration of liquid bitumen)	No reliable model available	Annual heat sum > 25°C (hours x Kelvin) [8]

Most mechanistic-emperical design models for fatigue (bottom up) cracking of flexible pavements use the weighted mean annual air temperature T_{wmaa} as climate parameter. Corresponding design guidelines provide the weight factors for calculating T_{wmaa} from monthly averages. The ME-PDG method [7] uses continuous temperature records from discrete observation stations. Most design methods and guidelines apply to standard pavement constructions and standard materials. Advanced models will be required for analysing long term effects on non-standard constructions and materials, e.g. high albedo pavements. The advanced models need to explicitly consider temperature distribution in the pavement structure as a function of air temperature throughout the day.

The ME-PDG method relies on empirical models for estimating the progress of top-down cracking and rutting originating in the bituminous layers. These models have been calibrated for a wide variety of climate zones and pavement types in the US.

Note that the value of T_{wmaa} for a pavement design must be weighted and averaged over the entire design service life of the pavement because the increase in mean annual temperature progresses gradually. The value of T_{wmaa} should not be taken equal to the value of T_{wmaa} in the current climate increased by the projected change of the mean annual temperature.

Experience suggests that more than absolute maximum temperature, pavement structure problems arise from high night temperatures (> 25°C). The high night temperatures prevent the pavement from cooling down at night and allow the heat to penetrate deeper into the pavement.

According to the P2R2C2 report [8] the annual heat sum (annual amount of hours with temperature over 25 ^{o}C) will affect failure mechanisms occurring at the surface of the pavement, such as embrittlement, loss of surface texture and migration of liquid bitumen. Thus, the annual heat sum > 25 ^{o}C is considered the climate parameter for these failure mechanisms. Design models or empirical data relating this climate parameter to the amount of damage caused are lacking, however.

Rate of change of the climate change impacts
Many of the damage mechanisms acts through repetition, i.e. the damage thresholds are reached by many consecutive extreme weather events (hot days, heat waves) over the years, not by a single event. Also, all mechanisms depend on the combined action of high temperature and heavy traffic to develop.

The rate of rutting, loss of surface texture and fatting (migration of liquid bitumen) for a given pavement temperature and traffic load depends on asphalt viscosity, that increases exponentially with temperature. Thus, a limited number of extreme weather events per year can be responsible for a relatively fast increase in damage. The progress of damage should therefore be monitored yearly, preferably after the summer.

4.1.3 Step 2: Resilience of the asset in current situation
As stated before, traffic loading and temperature are the two most important causes of pavement deterioration. However, many deterioration mechanisms are accelerated by the action of moisture. Birth defects and poor maintenance will promote degradation. The pavements of many roads have evolved over time to meet the increased traffic demand. As a consequence, the pavement construction, foundation and materials in these roads are less than perfect, with lateral variations in response to traffic loads and changes in temperature and moisture. This makes a general assessment of the impacts of higher temperatures on pavements an impossible task.

The ELLPAG study on long-life pavements [5] presents an inventory of observed deterioration in flexible pavements in Europe. From the ELLPAG inventory it is clear that:
- Rutting is not limited to countries with a Mediterranean climate; this may be attributed to the use of different binders corresponding to the temperatures expected for the particular climate zone.

- Rutting originating in the bituminous layers and cracking initiated at the surface are not the most frequent damage mechanisms in countries with a Mediterranean climate. Loss of skidding resistance (not necessarily from liquid bitumen migration), longitudinal cracking in the wheelpath and cracking initiated at the bottom of the base course are the most frequent damage mechanisms.
- The heat related damage mechanisms mentioned above seem to be evenly distributed over all climate zones. Again, this may be attributed to the use of different binders adapted for the specific climate zone. Alternatively, heat is not the only cause of damage.

The report of the EU Joint Research Council [1] concludes that the decomposition of maintenance costs between the different weather stresses and resulting deterioration and damages highly depends on the local conditions. It is also impossible to reflect here on the details of deterioration types well known in road infrastructure engineering science. Such effects are documented in the specialised literature [9]. Even limiting the inventory to the bituminous road pavement case includes a variety of impacts (cracking, rutting, ravelling, pot-holing) and, within the category "cracking", distinction is made between transversal, longitudinal, crocodile cracking). In some cases, the effects can also result only indirectly from climate stressors. For instance, rutting effect in cold regions is aggravated by the use of studded tyres as used in winters, and also depends on the use of salt for de-icing [10].

For these reasons, a general assessment of the current capability of the assets at national or regional network level is not possible, given the large variety of construction types, traffic loads, moisture conditions, maintenance history and local climate. A typical scale over which these conditions can be considered to be homogeneous is probably in the order of kilometres to tens of kilometres.

Many models for the prediction of the current capability (i.e. service life) of pavements are empirical. This applies to models for the damage mechanisms age hardening (embrittlement), top-down cracking, rutting originating in the bituminous layers, loss of surface texture and fatting (migration of liquid bitumen). This implies that these models are valid for the current practice of construction and maintenance and the current climate. Any change in climate will therefore affect the capability, meaning there is no spare capability.

Some NRAs have observed that only fatigue cracking originating at the bottom of the base course (bottom up cracking) proceeds at a rate less than predicted by the empirical-mechanistic design model (ELLPAG, [5]). In most cases the true structural service life of pavements exceeds the design value. This implies there is a spare capability for this specific damage mechanism that can be estimated by estimating the residual structural service life of the pavement.

4.1.4 Step 3: Resilience of the asset in possible future situations

The P2R2C2 project [6] has made an assessment of the effects of higher temperatures on top-down cracking, cracking initiated at the bottom of the base course and rutting originating in the bituminous layers, using the ME-PDG models [7]. Although the program has been developed and calibrated for US conditions it is still considered to be useful for a comparative study.

The analyses show, for an increase in maximum summer temperature between 2 ^{o}C (Finland) to 9 ^{o}C (France):

- A general moderate increase in rutting and a high increase in top-down cracking for Spain, France and Poland, no change in bottom-up cracking (low volume roads)

- A general moderate increase in rutting, top-down and bottom-up cracking (high volume roads)

The results of the P2R2C2 study imply that climate change will predominantly affect rutting in the bituminous layers and top-down cracking. Since no spare capability exists for these damage mechanisms, any amount of climate change will have immediate effects on the amount of damage. The increase in bottom-up cracking can probably be accommodated by the spare capability in the current designs, for even high increases in maximum summer temperature.

The P2R2C2 study has not considered the damage mechanisms age hardening (embrittlement), loss of surface texture and fatting (migration of liquid bitumen). Since no spare capability exists for these damage mechanisms, any amount of climate change will have immediate effects on the amount of damage.

4.1.5 Step 4: Identification of applicable / appropriate adaptation measures

Table 36 presents a list of adaptation measures and their effects on different deterioration mechanisms for flexible pavements.

Note: the measures were selected in the database by applying the filter ’05-1 Cracking, rutting, embrittlement’ AND ’06-6 Decrease in skid resistance on pavements from migration of liquid bitumen’ AND ‘07-3 Impact on road works: decreased time window for paving’ in column C ‘Threat sub category’, and deselecting ‘Concrete pavements’ in column F ‘Asset type’.

Table 36: Adaptation measures

Nr.	Measure	Age hardening (embrittlement)	Top-down cracking	Cracking initiated at the bottom of the base course	Rutting originating in the bituminous layers	Loss of surface texture	Fatting (migration of liquid bitumen)
Legislation, regulations							
429	Revised standards for materials in surface courses	X	X		X	X	X
Maintenance and management							
417	Cold mill and overlay, thin surface patches	X	X	X	X		
430	Treat with hot fine aggregate					X	X
Monitoring							
420	Keep construction records	X	X	X	X	X	X
Planning							
423	Prepare contingency / emergency plans	X	X	X	X	X	X
Research							
416	Anti-oxidation additives	X	X				

Nr.	Measure	Age hardening (embrittlement)	Top-down cracking	Cracking initiated at the bottom of the base course	Rutting originating in the bituminous layers	Loss of surface texture	Fatting (migration of liquid bitumen)
418	Harvesting of heat energy from the pavement	X	X	X	X	X	X
419	High albedo pavements, heat shield pavements, water retention pavements	X	X	X	X	X	X
426	Real time weather and traffic models	X	X	X	X	X	X
544	Alternative mixtures for bituminous pavements and surface courses				X	X	X
Resilient construction							
427	Replace by more temperature resilient material	X	X	X	X	X	X
547	Restrict working in high temperatures				X	X	X
550	Working during the night				X	X	X
Traffic management							
422	Placing warning signs				X	X	X
415	Access restrictions		X		X	X	X
428	Rerouting		X		X	X	X
421	Modal shift	X	X	X	X	X	X
425	Real time traffic information		X		X	X	X

4.1.6 Step 5: Establishing a policy

Table 37 presents the measures for Loss of pavement integrity – Cracking, rutting and Loss of driving ability and Decrease in skid resistance on pavements from migration of liquid bitumen in the policy matrix.

The matrix was produced from the database by selecting the measures first and then applying the macro CTRL+y.

Table 37: Policy matrix for Loss of pavement integrity – Cracking, rutting and Loss of driving ability and Decrease in skid resistance on pavements from migration of liquid bitumen

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	PRO-ACTIVE ATTITUDE: Prepare contingency / emergency plans						
	Robust construction		PREVENTION: Restrict working in high temperatures / Revised standards for materials in surface courses / Working during the night					
	Legislation, regulations							
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Replace by more temperature resilient material					
	Maintenance and management							CORRECTIVE MAINTENANCE AND REPLACEMENT: Cold mill and overlay, thin surface patches / Treat with hot fine aggregate
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Access restriction / Modal shift / Placing warning signs / Real time traffic information / Real time traffic information / Rerouting and guidance / Speed limits					
	Capacity building							
	Monitoring	MONITORING AND PREDICTION: Keep construction records						
	Research	RESEARCH: Alternative mixtures for bituminous pavements and surface courses / Anti-oxidation additives / Harvesting of heat energy from the pavement / High albedo pavements, heat shield pavements, water retention pavements / Preventive information / Real time weather and traffic forecast						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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4.1.7 Step 6: Assessment of consequence criteria for measures

Table 66 in Annex C present the assessment of the consequences of implementing the measures for Loss of pavement integrity – Cracking, rutting and embrittlement and Loss of driving ability – Decrease in skid resistance on pavements from migration of liquid bitumen.

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts. E.g. the impact of flooding on availability is more serious than a reduction of driving ability in a heavy rainstorm.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

4.1.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. 'Do minimum' strategy: a combination of the Pro-active attitude', Corrective maintenance and management and Traffic management policies in Table 37. The 'Pro-active attitude' policy implies the preparation of contingency plans. The Corrective maintenance and management policy implies that minimum safety standards are safeguarded at all times. Traffic hindrance is not paramount, nor is life cycle cost. Maintenance operations can remain more or less the same, although the interval of time between maintenance actions is likely to decrease. The Traffic management policy may involve placing signs for warning road users for marginally safe road conditions, but also imposing access restrictions for HGVs on hot days.
2. 'Future-proof designs' and 'Update operating procedures' strategies: a combination of Upgrading, Prevention and Monitoring and prediction policies of Table 37. The upgrading policy implies replacement of the damaged upper layers by temperature resilient material as part of regular maintenance works. The prevention policy implies changing specifications of all materials for new construction and maintenance. According to the P2R2C2 study [11] the rate of climate change is such that it can be accommodated within the usual service lives of surface layers and pavements, using existing pavement materials. Therefore, the Retro-fit solutions strategy does not apply. There will be a cost increase from using more heat-resistant binders.
3. 'Monitoring' strategy: this strategy will build up a knowledge base of deterioration models and the impacts of site factors, allowing better informed decisions for maintenance and upgrading. The monitoring may also include the socio-economic impacts of implementing or not implementing adaptation measures. This strategy thus serves the decision making between strategies, and the selection of measures in a strategy.
4. 'Research' strategy: this strategy aims at improving the measures implemented in the first two strategies with respect to cost-effectiveness, traffic hindrance, road user safety or network operation. The research may include materials and construction methods, early warning systems and socio-economic models.

At present, most NRAs adopt the 'Do minimum' strategy, and some NRAs have started adapting their material specifications as part of the 'Future-proof designs' strategy (CEDR, [2]).

The decision to adopt a strategy or shift from one strategy to another can be based on the following considerations:

- The Monitoring strategy is a no-regret option that facilitates further decision making.

- The impact of higher temperatures on pavements will depend on poorly known site specific factors, uncertainty in climate change projections and socio-economic developments. All decisions should therefore be based on impact studies considering all these factors.
- In the ‘Do minimum’ strategy, cost-benefit studies (including socio-economic cost) will support decisions between corrective maintenance and traffic management strategies imposing access restrictions for HGVs.
- For upgrading existing roads for an additional service life of 10-20 years, cost-benefit studies will help decide between maintaining current material specifications and applying materials that are more resilient to higher temperatures, i.e. a change to the ‘Future-proof designs’ strategy. The selection of more resilient materials will depend on the anticipated development of temperature over the additional service life, using present climate change projections. The required adaptation in material specifications can be achieved with existing binders and mix designs for most climate zones in Europe (P2R2C2 [11]).
- For new construction of roads with service lives of 30-50 years, cost-benefit studies can support the decision to change to the ‘Future-proof designs’ strategy. Cost-benefit studies need to consider uncertainty explicitly, both in climate change and in traffic volume. The latter is probably most influential.
- Cost-benefit studies for specific innovative measures can be initiated as part of the ‘Research’ strategy, to demonstrate the potential of measures aimed at reducing pavement temperature (P2R2C2 [11]).

4.1.9 Step 8: Stakeholders to be involved

The main stakeholder is the NRA. Funding agencies need to be aware of the additional cost for adaptation, and the impacts of the ‘Do minimum’ strategy.

Innovative pavements with lower temperatures may help reduce urban heat island effect. The additional benefits of this measure can be explored with the involvement of local authorities.

4.1.10 Step 9: Existing knowledge gaps

Climate variables
The relevant climate variables for heat stress on bituminous and semi-rigid pavements and the required temporal and spatial resolution of given below.

Table 38: Climate variables for heat stress on bituminous and semi-rigid pavements

Climate variable	Unit	Temporal resolution	Spatial resolution
Threat: Loss of pavement integrity – Cracking, rutting, embrittlement			
Annual heat sum > 25°C	hours x Kelvin	days	10 km
Records of mean monthly air temperature / continuous temperature records	°C	months / days	10 km
Threat: Loss of driving ability – Decrease in skid resistance on pavements from migration of liquid bitumen			
Annual heat sum > 25°C	hours x Kelvin	days	10 km

Projections for these climate variables need to be available at the correct temporal and spatial resolution.

Upcoming measures
Measures in the Research category of the database are:
- Harvesting of heat energy from the pavement
- Anti-oxidation additives
- High albedo pavements, heat shield pavements, water retention pavements
- Real time weather and traffic models
- Early warning, monitoring and prediction systems for road integrity and trafficability

These measures apply to both the threats Loss of pavement integrity – Cracking, rutting, embrittlement and Loss of driving ability due to extreme weather events – Decrease in skid resistance on pavements from migration of liquid bitumen.

The P2R2C2 study [11] describes the current situation regarding the development of the first three measures. Test sections with different techniques exist; no systematic evaluation of their performance has been performed yet. Development of the last two measures is taking place, although the integration of weather, traffic and prediction models has not yet been achieved.

The CEDR study [2] identifies the need for socio-economic models for the impact of adaptation to higher temperatures.

Data to be collected in order to assess the resilience of the asset
The data that need to be collected in order to understand the current capability of the asset and predict the future capability are given below.

Threat: Loss of pavement integrity – Cracking, rutting, embrittlement
- Construction records: age of bituminous layers; thickness of pavement, foundation and embankment layers, type of materials and material properties
- Drainage conditions, depth to groundwater table
- Maintenance records: rate of development of cracking, rutting, aggregate loss
- Records of climate variables

Threat: Loss of driving ability – Decrease in skid resistance on pavements from migration of liquid bitumen
- Construction records: age of surface course; type of material and material properties
- Maintenance records: rate of development of damage, loss of skid resistance
- Records of climate variables

4.1.11 Step 10: Time to market of upcoming techniques
The technology readiness level (TRL) of the measures is estimated as:
- Harvesting of heat energy from the pavement – TRL6: prototype demonstrated in relevant environment
- Anti-oxidation additives – TRL 5/6: component validation in relevant environment / prototype demonstrated in relevant environment
- High albedo pavements, heat shield pavements, water retention pavements: TRL 8: system completed through test and demonstration
- Real time weather and traffic models – TRL 8: system completed through test and demonstration

- Early warning, monitoring and prediction systems for road integrity and trafficability – TRL 6: prototype demonstrated in relevant environment

The FEHRL Resilient Road roadmap [3] estimates the following times to market:
- Anti-oxidation additives – R&D 8 years, demonstration 3 years; time to market 2012-2024 (12 years)
- High albedo pavements, heat shield pavements, water retention pavements: R&D 5 years, demonstration 3 years; time to market 2012-2020 (8 years)
- Real time weather and traffic models – R&D 5 years, demonstration 5 years; time to market 2012-2022 (10 years)
- Early warning, monitoring and prediction systems for road integrity and trafficability – R&D 5 years, demonstration 5 years; regulatory framework 3 years; time to market 2012-2025 (13 years)

Harvesting of heat energy from the pavement is not mentioned in the FEHRL roadmap. Based on the TRL and the estimates for other measures in the FEHRL roadmap, the estimated time to market for this measure will be in the order of 12 years.

4.2 Heat stress on concrete pavements

4.2.1 Step 0: Relevance to the road owner

All around Europe temperatures will increase as a consequence of climate change, resulting in pavement deteriorations:

- Increased cracking, rutting, embrittlement of bituminous binders, loss of surface texture, migration of liquid bitumen in bituminous and semi-rigid pavements, due to higher summer temperatures;
- Increased thermal expansion of concrete pavements, due to higher summer temperatures;
- Increased cracking of pavements after loss of bearing capacity by spring thaw, due to higher winter and spring temperatures;
- A decrease in utility of (unimproved) roads that rely on frozen ground, due to higher winter and spring temperatures.

Positive impacts from higher winter and spring temperatures are:

- A decrease in costs for de-icing;
- A decrease in low temperature cracking;
- A decrease in frost heave, because of fewer frost-thaw cycles;
- A decrease in damage from studded tyres;
- A decrease in aggregate loss and unbounded pavement layers because of frost.

This chapter deals with damage to cement concrete rigid pavements, due to higher summer temperatures. The impact is also referred to as “heat stress in rigid pavements”.

The damage from higher summer temperatures will cause a decrease in availability due to maintenance works, a reduction in driver safety because of loss of skidding resistance by liquid bitumen migration and increased aquaplaning in ruts of asphalt wearing courses, an increase in maintenance cost, and potential loss of confidence of the public in the ability of the road owner to deal with climate change impacts.

The report of the EU Joint Research Council [1] compares weather and climate induced infrastructure deterioration to deterioration due to traffic loading. Separating the two main factors for pavement degradation (weather conditions and traffic) is rather difficult. Therefore, the faction of national aggregated maintenance costs attributable to weather cannot be unequivocally assessed. Considering a 30%-50% contribution from weather conditions to total pavement deterioration for Europe would represent from 8 to 13 billion euros/year weather-induced costs for Europe. This number represents frost-thaw, precipitation and heat induced damage. In hot climates such as in Australia, temperature-related costs account for 36% of current maintenance costs for roads [4]. This number includes both asphalt and concrete pavements.

Concerns of the PEB members

The PEB members identified the following specific road owner’s problems related to heat stress in concrete pavements:

- How will climate change affect the service life of a specific road? Will there be any dramatic changes due to climate change? → see chapter 4.2.2
- How can one limit compression failures, cracks, joints damages, etc.? Should one look at design rules? Materials? → see chapter 4.2.5
- Concerning the impacts of higher pavement temperatures – can one wait until the next planned paving to introduce a better pavement type? → see chapter 4.2.8

Further issues are also related to rigid pavements as here under mentioned.

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs. Nine out of eleven NRAs consider higher temperatures as a serious risk. Hungary and Spain specifically mention problems related to deformation and durability of flexible pavements. French, Italian and Spanish NRAs feel a need for research on the impact of heat on pavements. The Swedish NRA identifies the need for a socio-economic study concerning what model to use in the future: strengthen the roads, repair them afterwards, or not allow heavy traffic during the winter.

Rigid pavements types
Rigid pavements comprise a cement concrete layer, the main structural element, laid onto a bound or unbound subbase layer. Four types of rigid pavements can be distinguished:

- “Californian” slabs with no joint reinforcement also called Jointed Unreinforced Concrete (URC) in the TRL study for the UK Department of Transport [33];
- Slabs equipped with dowels for joint reinforcement and improved load transfer between the slab edges also called Jointed Reinforced Concrete (JRC) by TRL;
- Continuously Reinforced Concrete Pavements (CRCP) that contains a continuous longitudinal steel reinforcement with no intermediate expansion or contraction joint. CRCP can be used either as surface layer or as base layer covered with an asphalt surface layer referring to Continuously Reinforced Concrete Base (CRCB) in the TRL study.

Jointed slab pavements mainly suffer from progressive defects which occur at the joints and generate slab faulting, resulting in evenness defects and increased maintenance costs to joints and slabs.

CRCP was developed to overcome the problems associated with joints. Thermal stresses within the concrete slab are relieved by the shrinkage transverse cracks which are held tightly closed by the steel reinforcement. The elimination of joints within the slab enhances the structural integrity of the pavement and reduces the amount of water penetrating into the pavement structure and the associating pumping of fines materials, leading also to enhanced foundation durability.

The asphalt surface layer on CRCP (that becomes CRCB) improves its ride ability in terms of evenness and noise reduction.

Impacts on rigid pavements
The study of TRL for the UK Department of Transport [33] lists the following effects of increased summer temperatures on rigid pavements, for Jointed Unreinforced Concrete (URC), Jointed Reinforced Concrete (JRC) and Continuously Reinforced Concrete Pavements (CRCP).

Curling and warping (URC, JRC, CRCP and CRCB)
Thermal gradients in concrete pavements can create uneven internal stresses which can then give rise to curling or warping, sometimes called hogging, of the slabs. These can be compounded by loading from passing traffic. Large changes in temperature generate thermal contraction and expansion of the slabs which, if not taken into consideration at the design stage, can generate unacceptably large longitudinal internal stresses and excessive movements at joints.

The effect of climatic conditions on road temperature in rigid conditions has been determined on three sections of rigid pavements in the UK. Temperatures measured at the top of the concrete slabs are considered to better reflect the temperatures which will have the greatest influence on the thermal movements at concrete surface cracks. The results on CRCP showed that the maximum monthly temperature at the top of the layer was 5°C greater than the air temperature.

With the requirement to cover concrete surfaces with asphalt, higher temperatures in the underlying concrete may be created. The specific effects on concrete of an overlying layer at a higher temperature have yet to be assessed. The coarse aggregate has the greatest volume of the concrete constituents, and so its coefficient of expansion greatly influences the thermal properties of the concrete.

Cracking

The tensile stresses which develop in reinforced concrete slabs can be relieved by thermally induced transverse cracks. This feature is the modus operandi of a CRCP which is designed to form transverse cracks at regular intervals. The transverse cracks are kept tightly closed by the reinforcement, which ensures structural integrity, good load transfer and little amount of surface water reaching the foundation layers and subgrade.

The spacing of the transverse cracks is a function of the climatic conditions at the time of paving. The transverse crack pattern in a CRCP or CRCB is an important factor for a satisfactory long-term performance. When transverse cracks are induced at large spacing, the cracks themselves may be wide, resulting in reduction of aggregate interlock and higher stresses on the longitudinal steel reinforcement, which may rupture and provide a passageway for surface water to penetrate the lower layers. Transverse cracks which are induced at close spacing may be connected by longitudinal cracking and can lead to blocks of concrete that become loose and break away from the surface, commonly known as punch-out. CRCP and CRCB laid during unusually high summer temperature can lead to more severe cracking patterns and related deteriorations during the cold periods.

Reflexion cracking is considered to be the main pavement distress for overlaid concrete pavements. Reflexion crack spacing and crack width influence the structural integrity and the durability of the pavement by providing a route for surface water to penetrate the steel reinforcement and the underlying materials. These cracks get open and close with temperature.

When a CRCP slab is overlaid with asphalt surfacing, an improved performance can be achieved by the ability of the overlay to resist reflection cracking and rutting through traffic loadings.

Joints

Transverse joints, either contraction or expansion, are placed at regular intervals in a length of jointed concrete to relieve the tensile stresses induced by thermal changes during the initial curing period, and then from the effects of daily and seasonal temperature changes.

In CRCP or CRCB, no transverse joints are placed within the main slab, but only at the terminations since the amount of horizontal movement at the end of a slab due to the seasonal temperature variations and thermal shrinkage can be significant and reach 20 mm between the summer and winter periods. If not taken into consideration, these movements can cause damage to adjacent pavements and structures. The two existing systems of CRCP or CRCB slabs terminations are ground beam anchorage or wide-flange steel beam.

Both of them require expansion joints between transition slabs to accommodate any residual or unforeseen movement of the slab end.

The long-term performance of well-constructed joints in a pavement is related to the amount of thermal movements from climatic conditions, and has a direct effect on the overall performance of the pavement by allowing a joint to perform satisfactorily. It is important that adequate load transfer efficiency is maintained, differential movements of the slab either side of the joint is kept to a minimum, and that good support is provided to the slabs at the joints.

Compression failures

To ensure the joints are working as intended, the joint gap should be free to open and close and the joints kept permanently sealed to avoid ingress of water and detritus. Water penetration can lead to loss of subbase support and accumulation of detritus in the joint gap will impair the thermal movements of the joint, which could lead to the situation known as compression failure or “blow-up”.

Various forms of weakness introduced into pavements have been identified as making them more prone to compression failure. These include temporary repairs using materials that exhibit poor compressive resistance, poor compaction over the slab depth during construction and incompressible inserts for crack inducement used at joints. Any eccentricities at the joint section will offset the centre of thrust away from the neutral axis of the slab, thus making the joint more prone to buckling failure. The presence of weak material at this section, such as poorly compacted concrete or temporary repair material will increase the stress in the remainder section.

Compression failures have also been noticed where a series of transverse joints have not been constructed satisfactorily and so do not allow any thermal movement. In this case, the additional thermal movements cannot be accommodated in those joints that are freely moving. It may be the case that compression failures are more prevalent after colder winters, when joints are more open and when there is greater opportunity for the ingress of grit, especially if followed by unusually high summer temperatures.

Damage at terminal joints (CRCP, CRCB)

The temperature at the time of construction will influence the initial movements of the transverse joints. Slabs laid in period of high temperature will be subjected to a larger gap across the joint in winter when compared to slabs laid in cooler summer weather. For a CRCP constructed in winter, an initial seasonal summer expansion at the end of the slab will occur.

An important consideration in developing designs for CRCP pavements is the amount of thermal movement at the terminations to a slab and at the expansion joints. The seasonal thermal movements across a joint are expected for a temperature range of 30°C which is the maximum range of temperature likely to occur in average year in Europe. Expressing the seasonal thermal movement across a joint for a temperature range of 30°C may no longer be appropriate with the effect of global warming on concrete temperatures. Temperatures recorded at CRCP indicate that a value of at least 40°C may be more appropriate. With respect to the seasonal thermal joints movements, the amount of movement during a twelve month period would then be equivalent to an increase of 33% when compared to with the movements calculated at a 30°C range. At the CRCP terminations, the expansion joint movement would exceed the recommendations of the joint sealant manufacturers.

It has been found that CRC slabs can extend by progressively smaller distances in summer relative to their previous summer position, possibly due to detritus collected in the crack opening which, in summer during thermal expansion, causes the slab to extend more than at the previous summer. If the expansion results in only little movement at the joint and the slab is fully restrained at the ends, compressive forces can build up in the slab, leading to compressive failure. The risk of this occurring is potentially greater in periods of extremely high summer temperatures.

Terminal joints of continuously reinforced pavements may exhibit excessive movements at transitions to other pavement types or to bridges. In that case, the additional thermal movements exert an unforeseen load damaging to pavement or bridge deck. Damage to the joint seals may result in clogging of the joint gap with debris, leading to additional compression failures.

Effects of water
For all scenarios of climate change, mean annual precipitation increases in northern Europe and decreases in the south. An increase in the intensity of daily precipitation is likely, even in areas with projected less mean precipitation. The probability of extreme precipitations might be multiplied in some regions in northern Europe.

Concrete is generally regarded as impervious to water. However, jointed pavements are designed to have discontinuities in the form of joints and CRCP has discontinuities in the form of naturally formed transverse cracks. Water can enter the underlying layers through the poorly maintained joint seals or through wide surface cracks. Under traffic loading, water penetrating the lower layers can result in pumping of fine material to the road surface through joints and cracks from underneath the concrete slabs as a result of inadequate slab support. The effects of water under a slab are:

- Weakening of the foundation and the subgrade by reducing the stiffness of the layers;
- Differential vertical movements at joints leading to stepping;
- Erosion of the unbound subbase and/or subgrade material leading to voiding and decreasing structural support.

Whilst concrete, as a material, is largely unaffected by periods of intense rain, the area for concern will lie with water penetrating the lower layers and drainage quality to prevent the water from becoming a hazard to the road users.

Water and temperatures changes could greatly influence the durability of concrete. Generally all forms of physical and chemical deteriorations of concrete involve water in one way or another. Water acts as a media for carrying out aggressive substances, such as chloride and sulphate ions, from surrounding environment into the concrete. The presence of water in concrete influences its hydration and shrinkage properties at early ages and causes damage due to freeze-thaw. High temperatures could accelerate any chemical reactions that take place in concrete as well as the rate of penetration of harmful substances. The main durability concerns related to concrete pavements are reinforcement corrosion, alkali-silica reaction and sulphate attack.

Discontinuities in reinforced-concrete pavements, in forms of cracks and joints, have the potential to allow the penetration of de-icing water causing the corrosion of the steel reinforcement. The corrosion of reinforcement is a fairly slow process, usually taking many years to develop, but could be accelerated in warmer and wetter weather. When steel corrodes, the cross sectional area of the steel is reduced due to the formation of brown rust. The rust formed occupies several times greater volume than the original reinforcement and therefore generates an internal pressure in the concrete that can result in cracking.

Alkali silica reaction (ASR) is a chemical reaction that occurs between the alkaline pore solution of the cement paste and certain form of silica present in the aggregate, forming a gel product. With the availability of moisture, the gel can expand causing internal stress and consequently cracking. Experience in the USA on the use of recycled concrete aggregate in concrete pavements could increase the risk of ASR, especially if ASR has previously damaged the initial concrete. The ASR risk can be much reduced by the use of low-alkali-cements and cement replacement materials such as fly ash and slag.

Sulphate salts, when present in concrete, react with hydrated lime causing expansive products. The expansion increases under wet conditions and high temperatures. The consequences of sulphate attack include disruptive expansion, cracking and loss of cohesion and strength of concrete. Appropriate selection of concrete constituent materials and separation of the concrete pavement layer from contaminated ground water can greatly minimize the risk of sulphate attack.

Impacts on bituminous wearing courses on rigid pavements
The here above mentioned study of TRL for the UK Department of Transport [33] lists the following effects of increased summer temperatures on asphalt materials overlaying rigid pavements. These effects are the same as already listed for flexible pavements.

Age hardening (embrittlement) and top-down cracking
Age hardening increases the viscosity of the binder and depends on temperature, time and the bitumen film thickness. Premature cracking will result from thermal and traffic induced stresses and strains. Higher average temperatures increase the rate of oxidative age hardening and will therefore accelerate the appearance of surface cracks.

Rutting originating in the bituminous layers
At high temperatures, asphalt becomes more susceptible to deformation and rutting is more likely to occur, particularly on highly trafficked roads and at low traffic speeds. Research has found that the majority of rutting in the asphalt surfacing occurs on a few days of the year, when the temperature of the road surfacing exceeds 45°C. Rutting resistance can be increased by using fully crushed aggregates and an aggregate grading that provides a good aggregate skeleton and/or a binder with better high-temperature properties and good mixture design.

Loss of surface texture
Low viscosity binders will allow the penetration of surface chippings on hot days, causing a loss of surface texture and reduced skid resistance.

Fatting (migration of liquid bitumen)
Migration of low viscosity binder to ruts will cause a reduction of skid resistance.

Bitumen stripping
Stripping is the separation of asphalt binder film from the aggregate surface due to the action of moisture, exacerbated by traffic. Stripping is accelerated by warm moist conditions and it can lead to localized areas of deteriorations and eventually to total disintegration of the asphalt layer. Generally basic aggregates such as limestone are less prone to stripping than acid aggregates such as granite and quartzite. More viscous binders are less prone to be stripped. Additives such as amine and hydrated lime can reduce the aggregate’s vulnerability to stripping.

4.2.2 Step 1: Definition of the relevant climate variable from design guidelines

Traffic loading and temperature are the two most important causes of pavement deterioration. This chapter gives models commonly used for pavement design with respect to the different deterioration mechanisms. Most models allow the separation of effects of traffic loading and temperature.

Table 39 lists the design models and climate parameters for the heat related deterioration mechanisms in rigid pavements.

Table 39: Design models and climate parameters for rigid pavements

Deterioration mechanism	Design model	Climate parameter
Curling and warping	ME-PDG [7]	Annual heat sum > 25^{o}C (hours x Kelvin) [8]
Slab cracking (JRC and URC)	ME-PDG [7]	Annual heat sum > 25^{o}C (hours x Kelvin) [8] and rainfalls record
Punch-out (CRCP)	ME-PDG [7]	
Slab faulting (JRC and URC)	ME-PDG [6], [7]	
Compression failures	No reliable model available	
Damage at terminal joints (CRCP and CRCB)	No reliable model available	Annual heat sum > 25^{o}C (hours x Kelvin) [8]
Effects of water	No reliable model available	Annual heat sum > 25^{o}C (hours x Kelvin) [8]

The ME-PDG design model considers the following parameters:

- For JRC and URC, mean transverse slab faulting is a measurement of the differential deflection across the joint. This distress under heavy traffic can be caused by poor joint load transfer efficiency, free moisture below the concrete slab, erosion of the subbase material and upward curling of the slab [7]. Faulting is calculated in inches.
- Bottom-up transverse cracking is caused by a tensile strength at bottom of the JRC or URC slab, midway before two transverse slabs. Repeated heavy axle loading and high positive temperature gradient between top and bottom of the slab can cause fatigue damage to occur along the bottom of the slab. This fatigue damage results in transverse cracks that spread to the surface.
- Top-down transverse cracking is caused by fatigue damage at the top of the JRC or URC slab. A high negative temperature gradient (bottom of slab warmer than top) combined with simultaneous high axle loading at opposite ends of a slab produces a high tensile stress and a crack at the top of the slab initiating at the surface of the pavement. Bottom-up transverse cracking and top-down transverse cracking are combined and calculated as percent of slabs cracked.
- For CRCP, the predicted number of medium and high severity punch-outs per mile is computed based on the number of predicted cracks, predicted mean crack width, etc.

The ME-PDG [7] computational methodology uses the finite element analysis program ISLAB2000 for pavement responses that are converted to distress prediction calibrated using data from existing pavement databases, with most information coming from the long term pavement performance (LTPP) database which provides long term data analysis for a wide range of structures containing a variety of material, traffic and environmental conditions. The ME-PDG method uses continuous temperature records from discrete observation stations.

Most design methods and guidelines apply to standard pavement constructions and standard materials. Advanced models will be required for analysing long term effects on non-standard constructions and materials, e.g. high albedo pavements. The advanced models need to explicitly consider temperature distribution in the pavement structure as a function of air temperature throughout the day.

Rate of change of the climate change impacts
Many of the damage mechanisms act through repetition, i.e. the damage thresholds are reached by many consecutive extreme weather events (hot days, heat waves) over the years, not by a single event. Also, all mechanisms depend on the combined action of high temperature and heavy traffic to develop.

Thus, a limited number of extreme weather events per year can be responsible for a relatively fast increase in damage. The progress of damage should therefore be monitored yearly, preferably after the summer.

4.2.3 Step 2: Resilience of the asset in current situation
As stated before, traffic loading and temperature are the two most important causes of pavement deterioration. However, many deterioration mechanisms are accelerated by the action of moisture. Birth defects and poor maintenance will promote degradation. The pavements of many roads have evolved over time to meet the increased traffic demand. As a consequence, the pavement construction, foundation and materials in these roads are less than perfect, with lateral variations in response to traffic loads and changes in temperature and moisture. This makes a general assessment of the impacts of higher temperatures on pavements an impossible task.

The report of the EU Joint Research Council [1] concludes that the decomposition of maintenance costs between the different weather stresses and resulting deterioration and damages highly depends on the local conditions. It is also impossible to reflect here on the details of deterioration types well known in road infrastructure engineering science. Such effects are documented in the specialised literature [9].

For these reasons, a general assessment of the current capability of the assets at national or regional network level is not possible, given the large variety of construction types, traffic loads, moisture conditions, maintenance history and local climate. A typical scale over which these conditions can be considered to be homogeneous is probably in the order of kilometres to tens of kilometres.

4.2.4 Step 3: Resilience of the asset in possible future situations
Provided that concrete materials contain no deleterious substances, changes in climate conditions are unlikely to influence the durability of rigid pavements. Climate changes would include warmer summers, increased rainfalls and less spells of frost. Whilst water and heat could accelerate chemical reactions in concrete, appropriate selection of constituent materials could greatly minimize these harmful reactions. Current practice of covering the surface of concrete pavement with asphalt surfacing should reduce the ingress of deleterious substances from the surrounding environment and enhance its durability. The reduced spells of frost periods should also contribute to enhanced durability by reducing the amount of de-icing salts used on pavements.

The following considerations and adaptation measures are recommended for construction and maintenance of rigid pavements:

Compression failures
- Inspect and monitor the condition of joint seals at a regular frequency;

- Ensure joints are sealed so dust and debris cannot penetrate and prevent expansion;
- Replace defective joint seals to ensure that sealants are adequately bonded and adhering to the concrete slabs at the joint detail and are ductile to expand as a result of higher temperatures. The utilization of upgraded joint sealant may be considered to provide future improved performance to cope with the potential greater joint movement;

Concrete expansion

- For new construction or replacement of slabs, the concrete coarse aggregates may need to be restricted to those with a low coefficient of expansion to reduce the amount of thermal movements across cracks and joints;
- Construction of concrete pavements with a greater gap can also be considered for new or replacement slabs;

Concrete construction

- At high temperatures, concrete mixes may require to be re-evaluated for workability characteristics and curing arrangements including the curing time. This may well require the use of selected additives to modify the basic concrete mix.
- Newly paved concrete will need more protection from solar heat during the initial curing period, and paving restricted in periods of excessively high temperatures.
- Concrete mixtures may no longer need to be air entrained to protect against freeze/thaw effects.
- A review of concrete pavement design in countries with hotter climatic conditions could be considered.

Asphalt surface course

Many rigid pavements have been overlaid by an asphalt wearing course. Due to their black colour, asphalt materials have a greater solar absorption when compared to rigid concrete and asphalt overlay is more problematic at higher temperatures. The recommendation of using exposed aggregate in open textured concrete surface course can be considered.

4.2.5 Step 4: Identification of applicable / appropriate adaptation measures

Table 40 presents a list of adaptation measures and their effects on different deterioration mechanisms for rigid pavements.

Note: the measures were selected in the database by applying the filter '05-1 Cracking, rutting, embrittlement' AND '05-5 Thermal expansion of pavements' AND '06-6 Decrease in skid resistance on pavements from migration of liquid bitumen' AND '07-3 Impact on road works: decreased time window for paving' in column C 'Threat sub category', and selecting 'Concrete' AND 'All road infrastructure' AND 'Pavements: bituminous, concrete, semi-rigid' in column F 'Asset type'.

Table 40: Adaptation measures

Nr.	Measure	Curling and warping	Slab cracking (JRC and URC)	Punch-out (CRCP)	Slab faulting (JRC and URC)	Compression failures	Damage at terminal joints (CRCP and CRCB)	Effects of water
Legislation, regulations								
429	Revised standards for materials and construction process in concrete pavements	X	X	X	X	X	X	X
477	Revised standards for heat resilient pavements, including effects of dark surface courses, joint width in JCP, terminal joint design in CRCP	X	X	X	X	X	X	
Maintenance and management								
472	Appropriate maintenance of joint seals to prevent clogging of joints		X		X	X		X
Monitoring								
420	Keep construction records	X	X	X	X	X	X	X
Planning								
423	Prepare contingency / emergency plans	X	X	X	X	X	X	X
Research								
418	Harvesting of heat energy from the pavement	X				X	X	
419	High albedo pavements, heat shield pavements, water retention pavements	X				X	X	
424	Preventive information	X				X		
426	Real time weather and traffic models	X	X	X	X	X	X	X
474	Heat resistant concrete fixings						X	
545	Alternative mixtures for concrete pavements	X	X	X		X		
Resilient construction								
478	Upgrade joint seal composition		X		X	X		X
479	Use a low coefficient of expansion coarse aggregates in the mixture	X	X		X	X	X	
546	Modify the concrete mixture to ensure adequate workability and curing time	X	X	X	X	X		X
548	Restrict working in high temperatures	X	X	X	X	X	X	X
549	Restrict concrete paving during periods of heavy rain							X
Traffic management								

Nr.	Measure	Curling and warping	Slab cracking (JRC and URC)	Punch-out (CRCP)	Slab faulting (JRC and URC)	Compression failures	Damage at terminal joints (CRCP and CRCB)	Effects of water
415	Access restrictions		X	X	X	X	X	X
421	Modal shift		X	X	X	X	X	X
422	Placing warning signs		X	X	X	X		X
425	Real time traffic information		X	X	X	X	X	X
428	Rerouting		X	X	X	X	X	X

4.2.6 Step 5: Establishing a policy

Table 41 presents the measures for Loss of pavement integrity – Curling and warping, slab cracking (JRC and URC), punch-out (CRCP), slab faulting (JRC and URC), compression failures, damage at terminal joints (CRCP and CRCB) and effects of water in the policy matrix.

Table 42 presents the measures for Loss of driving ability in case of asphalt overlay on top of the rigid pavement – Decrease in skid resistance on pavements from migration of liquid bitumen in the policy matrix.

Table 41: Policy matrix for Loss of pavement integrity – Curling and warping, slab cracking (JRC and URC), punch-out (CRCP), slab faulting (JRC and URC), compression failures, damage at terminal joints (CRCP and CRCB) and effects of water

STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
			In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
Planning for CCI&EWE							
Robust construction							
Legislation , regulations	**PRO-ACTIVE ATTITUDE: Prepare contingency / emergency plans**	**PREVENTION: Revised standards for heat resilient pavements, including effects of dark surface courses, joint width in JCP, terminal joint design in CRCP / Upgrade joint seal composition / Use a low coefficient of expansion coarse aggregates in the mixture / Modify the concrete mixture to ensure adequate workability and curing time / Restrict working in high temperatures / Restrict concrete paving during periods of heavy rain / Working during the night**					
Resilient construction							
Maintenance and management			**PREVENTIVE MAINTENANCE AND REPLACEMENT: Appropriate maintenance of joint seals to prevent clogging of joints**				
Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT: Access restriction / Modal shift / Placing warning signs / Real time traffic information / Access restriction / Rerouting and guidance**					
Capacity building							
Monitoring	**MONITORING AND PREDICTION: Keep construction records**						
Research	**RESEARCH: Preventive information / Harvesting of heat energy from the pavement / Heat resistant concrete fixings / Alternative mixtures for concrete pavements**						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

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Table 42: Policy matrix for Loss of driving ability – Decrease in skid resistance on pavements from migration of liquid bitumen in case of asphalt overlay

STAGES		PRO-ACTION	PREVENTION	PREPARATION: In preparation of an extreme event	PREPARATION: Just before an extreme event	RESPONSE: During an extreme event	RESPONSE: Just after an extreme event	RECOVERY: After an extreme event
OBJECTIVES		*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE	**PRO-ACTIVE ATTITUDE:** Prepare contingency / emergency plans						
	Robust construction		**PREVENTION:** Revised standards for materials in surface courses					
	Legislation , regulations							
	Resilient construction		**UPGRADE, RETROFIT, NEW CONSTRUCTION:** Replace by more temperature resilient material					
	Maintenance and management							**CORRECTIVE MAINTENANCE AND REPLACEMENT:** Cold mill and overlay, thin surface patches / Treat with hot fine aggregate
	Traffic management for CCI&EWE		**TRAFFIC MANAGEMENT:** Placing warning signs / Real time traffic information / Rerouting and guidance / Speed limits					
	Capacity building							
	Monitoring							
	Research	**RESEARCH:** Harvesting of heat energy from the pavement / Anti-oxidation additives / High albedo pavements, heat shield pavements, water retention pavements						

‘Do minimum’ and ‘Develop contingency plans’ strategy
‘Future-proof designs’, ‘Retrofit solutions’ and ‘Update operating procedures’ strategies
‘Monitoring’ strategy
‘Research’ strategy

4.2.7 Step 6: Assessment of consequence criteria for measures

Table 67 in Annex C presents the assessment of the consequences of implementing the measures for Loss of pavement integrity – Curling and warping, slab cracking (JRC and URC), punch-out (CRCP), slab faulting (JRC and URC), compression failures, damage at terminal joints (CRCP and CRCB) and effects of water in the strategy matrix.

Table 68 in Annex C presents the same assessment for implementation of the measures for Loss of driving ability in case of asphalt overlay on top of the rigid pavement – Decrease in skid resistance on pavements from migration of liquid bitumen in the strategy matrix.

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts. E.g. the impact of flooding on availability is more serious than a reduction of driving ability in a heavy rainstorm.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

4.2.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. ‘Do minimum’: a combination of the Corrective maintenance and management and Traffic management strategies in Table 41 and Table 42. The Corrective maintenance and management strategy implies that minimum safety standards are safeguarded at all times. Traffic hindrance is not paramount, nor is life cycle cost. Maintenance operations can remain more or less the same, although the interval of time between maintenance actions is likely to decrease. The Traffic management strategy may involve placing signs for warning road users for marginally safe road conditions, but also imposing access restrictions for HGVs on hot days.
2. ‘Keeping up with climate change’: a combination of Upgrading, Prevention and Monitoring and prediction strategies of Table 41 and Table 42. The upgrading strategy implies replacement of the damaged upper layers by temperature resilient material as part of regular maintenance works. The prevention strategy implies changing specifications of all materials for new construction and maintenance. According to the P2R2C2 study [11] the rate of climate change is such that it can be accommodated within the usual service lives of surface layers and pavements, using existing pavement materials. There will be a cost increase.
3. ‘Monitoring and prediction’: this strategy will build up a knowledge base of deterioration models and the impacts of site factors, allowing better informed decisions for maintenance and upgrading. The monitoring may also include the socio-economic impacts of implementing or not implementing adaptation measures. This strategy thus serves the decision making between strategies, and the selection of measures in a strategy.
4. ‘Research strategy’: this strategy aims at improving the measures implemented in the first two strategies with respect to cost-effectiveness, traffic hindrance, road user safety or network operation. The research may include materials and construction methods, early warning systems and socio-economic models.

At present, most NRAs adopt the ‘Do minimum’ overall strategy, and some NRAs have started adapting their material specifications as part of the ‘Keeping up with climate change’ overall strategy (CEDR, [2]).

The decision to adopt a strategy or shift from one strategy to another can be based on the following considerations:

- The monitoring and prediction strategy is a no-regret option that facilitates further decision making.
- The impact of higher temperatures on pavements will depend on poorly known site specific factors, uncertainty in climate change projections and socio-economic developments. All decisions should therefore be based on impact studies considering all these factors.
- In the 'Do minimum' strategy, cost-benefit studies (including socio-economic cost) will support decisions between corrective maintenance and traffic management strategies imposing access restrictions for HGVs.
- For upgrading existing roads for an additional service life of 10-20 years, cost-benefit studies will help decide between maintaining current material specifications and applying materials that are more resilient to higher temperatures, i.e. a change to the 'Keeping up with climate change' overall strategy. The selection of more resilient materials will depend on the anticipated development of temperature over the additional service life, using present climate change projections. The required adaptation in material specifications can be achieved with existing binders and mix designs for most climate zones in Europe (P2R2C2 [11]).
- For new construction of roads with service lives of 30-50 years, cost-benefit studies can support the decision to change to the 'Keeping up with climate change' overall strategy. Cost-benefit studies need to consider uncertainty explicitly, both in climate change and in traffic volume. The latter is probably most influential.
- Cost-benefit studies for specific innovative measures can be initiated as part of the 'Research' strategy, to demonstrate the potential of measures aimed at reducing pavement temperature (P2R2C2 [11]).

4.2.9 Step 8: Stakeholders to be involved

The main stakeholder is the NRA. Funding agencies need to be aware of the additional cost for adaptation, and the impacts of the 'Do minimum' strategy.

In urban areas, innovative pavements with lower temperatures may help reduce the urban heat island effect. The additional benefits of this measure can be explored with the involvement of local authorities.

4.2.10 Step 9: Existing knowledge gaps

Measures in the Research category of the database are:

- Harvesting of heat energy from the pavement
- Anti-oxidation additives (for asphalt wearing courses)
- High albedo pavements, heat shield pavements, water retention pavements
- Real time weather and traffic models

These measures apply to both the threats Loss of pavement integrity – Cracking, rutting, embrittlement and Loss of driving ability due to extreme weather events – Decrease in skid resistance on pavements from migration of liquid bitumen.

The P2R2C2 study [11] describes the current situation regarding the development of the first three measures. Test sections with different techniques exist; no systematic evaluation of their performance has been performed yet. Development of the last two measures is taking place, although the integration of weather, traffic and prediction models has not yet been achieved.

The CEDR study [2] identifies the need for socio-economic models for the impact of adaptation to higher temperatures.

4.2.11 Step 10: Time to market of upcoming techniques

The technology readiness level (TRL) of the measures is estimated as:

- Harvesting of heat energy from the pavement – TRL7: prototype demonstrated in a road with traffic
- Anti-oxidation additives – TRL 5/6: component validation in relevant environment / prototype demonstrated in relevant environment
- High albedo pavements, heat shield pavements, water retention pavements: TRL 8: system completed through test and demonstration
- Real time weather and traffic models – TRL 8: system completed through test and demonstration
- Early warning, monitoring and prediction systems for road integrity and trafficability – TRL 6: prototype demonstrated in relevant environment

The FEHRL Resilient Road roadmap [3] estimates the following times to market:

- Anti-oxidation additives – R&D 8 years, demonstration 3 years; time to market 2012-2024 (12 years)
- High albedo pavements, heat shield pavements, water retention pavements: R&D 5 years, demonstration 3 years; time to market 2012-2020 (8 years)
- Real time weather and traffic models – R&D 5 years, demonstration 5 years; time to market 2012-2022 (10 years)
- Early warning, monitoring and prediction systems for road integrity and trafficability – R&D 5 years, demonstration 5 years; regulatory framework 3 years; time to market 2012-2025 (13 years)

Harvesting of heat energy from the pavement is not mentioned in the FEHRL roadmap. Based on the TRL and the estimates for other measures in the FEHRL roadmap, the estimated time to market for this measure will be in the order of 12 years.

4.3 Pavement deterioration by spring thaw

4.3.1 Step 0: The road owner’s needs

Relevance to the road owner
As a result of climate change, temperatures will change all over Europe. More precipitation and milder temperatures during winter are likely to induce thaw-related problems in areas where the temperature periodically drop below zero degrees Celsius. This might cause cracking of the pavement due to thaw-induced settlement of the road base, while other areas might experience less problems with thaw-related cracks.

The damage from thaw-induced cracking of the pavement will cause a decrease in availability due to maintenance works, a reduction in driver safety because of uneven surfaces, an increase in maintenance cost, and potential loss of confidence of the public in the ability of the road owner to deal with climate change impacts.

The report of the EU Joint Research Council [1] compares weather and climate induced infrastructure deterioration to deterioration due to traffic loading. Separating the two main factors for pavement degradation (weather conditions and traffic) is rather difficult. Therefore, the faction of national aggregated maintenance costs attributable to weather can't be unequivocally assessed. Considering a 30%-50% contribution from weather conditions to total pavement deterioration for Europe would represent from 8 to 13 billion euros/yr weather-induced costs for Europe. This number represents frost-thaw, precipitation and heat induced damage. In hot climates such as in Australia, temperature-related costs account for 36% of current maintenance costs for roads [4].

Concerns of the NRAs
The PEB members identified the following specific road owner’s problems related to landslips and avalanches in a changed climate:

- How will climate change affect the service life of a specific road?
- How can cracks be limited?

The CEDR report on Climate change [2] presents an inventory of NRA concerns and research needs. Four out of ten NRAs, all in the Nordic countries and around the Alps, consider frost-thaw cycles as a serious risk. Affected countries call for research on effect on pavement conditions.

4.3.2 Step 1: Definition of the relevant climate variable from design guidelines
Frost-thaw cycles are the relevant climate parameters for cracking of pavement due to weakening of road base.

Rate of change of the climate change impacts
An increase of temperature zero-crossings are to be expected in areas where winter temperatures in current climate normally drops below zero but where future climate will make warmer temperatures more common. Areas where the future climate will give seasonally mean temperatures of around 0°C are to be most exposed for this type of impact.

4.3.3 Step 2: Resilience of the asset in current situation

To gain problems with movement in the road embankment due to thaw, three elements are necessary: frost susceptible soil (significant proportions of fine sediments such as clay or silt), subfreezing temperatures and water. An area with mean temperatures close to zero and with many freeze-thaw cycles is likely to be more exposed.

In areas where temperatures regularly drops below 0°C it's important that drainage systems are sufficient and that road embankments are made from non-sensitive materials. Particularly in older roads the material of the embankment might not be known and these are to be treated as potential risk areas.

4.3.4 Step 3: Resilience of the asset in possible future situations

A change of temperatures might change the areas where temperature zero-crossings get more or less common.

4.3.5 Step 4: Identification of applicable / appropriate adaptation measures

Table 43 presents a list of adaptation measures and their effects on cracking due to weakening of the road base by thaw.

Note: the measures were selected in the database by applying the filter '05-4 Cracking due to weakening of the road base by thaw' and respective 'category of measure'.

Table 43: Adaptation measures

Measure	**Cracking due to weakening of the road base by thaw**
Legislation, regulations	
Revised standards for (sub)base and subgrade materials, drainage	X
Resilient construction	
Partial reconstruction of pavement	X
Increase the thickness of structural layers	X
Maintenance and management	
Increase width of lane for removal of snow	X
Emergency repairs	X
Keeping the road drainage in good condition	X
Robust construction	
Artificial cooling and/or extracting heat from the embankment	X
Traffic management	
Access restriction	X

Measure	**Cracking due to weakening of the road base by thaw**
Modal shift	X
Real time traffic information	X
Rerouting and guidance	X
Speed limits	X
Monitoring	
Monitoring to detect potential problem areas, establish cause-impact relationships; maintain specific construction and maintenance records	X
Research	
Preventive information	X
Real time weather and traffic forecast	X

4.3.6 Step 5: Establishing a policy

Table 44 presents the measures for landslips and avalanches in the policy matrix.

The matrices were produced from the database by selecting the measures first and then applying the macro CTRL+y.

Table 44: Policy matrix for cracking due to weakening of road base

	STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
				In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
	OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
CATEGORY OF ADAPTATION MEASURE	Planning for CCI&EWE							
	Robust construction							
	Legislation , regulations		PREVENTION: Artificial cooling and/or extracting heat from the embankment / Revised standards materials in all layers, drainage					
	Resilient construction		UPGRADE, RETROFIT, NEW CONSTRUCTION: Increase the thickness of structural layers, using a more compact wearing course layer (SMA for example) / Partial reconstruction of pavement					
	Maintenance and management			PREVENTIVE MAINTENANCE AND REPLACEMENT: Keeping the road drainage in good condition / Keeping ditches and culverts free of snow and ice by means of good winter maintenance practices				CORRECTIVE MAINTENANCE AND REPLACEMENT: Preventive maintenance before winter such as increase the width of lane for removal of snow / Emergency repairs
	Traffic management for CCI&EWE		TRAFFIC MANAGEMENT: Access restriction / Modal shift / Real time traffic information / Rerouting and guidance / Speed limits					
	Capacity building							
	Monitoring	MONITORING AND PREDICTION: Monitoring to detect potential problem areas, establish cause-impact relationships; maintain specific construction and maintenance records						
	Research	RESEARCH: Preventive information / Real time weather and traffic forecast						

'Do minimum' and 'Develop contingency plans' strategy
'Future-proof designs', 'Retrofit solutions' and 'Update operating procedures' strategies
'Monitoring' strategy
'Research' strategy

4.3.7 Step 6: Assessment of consequence criteria for measures

Table 69 presents the assessment of the consequences of implementing the measures for landslides, debris flows, rock falls and avalanches respectively.

The reference for the assessment is the present climate and the present practice of road construction and operation. The assessment is not site specific. However, bigger threats will generally have bigger impacts.

The assessment of the impacts of the measures should be compared with the assessment of continuing the current way of construction and operation. This assessment is to be made by the NRA.

4.3.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

The following overall strategies can be identified for adaptation:

1. 'Do minimum' strategy: a combination of the Pro-active attitude', Corrective maintenance and management and Traffic management policies in Table 44. The 'Pro-active attitude' policy implies the preparation of contingency plans. The Corrective maintenance and management policy implies that minimum safety standards are safeguarded at all times. Traffic hindrance is not paramount, nor is life cycle cost. Maintenance operations can remain more or less the same, although the interval of time between maintenance actions is likely to decrease. The Traffic management policy may involve placing signs for warning road users for marginally safe road conditions, but also imposing access restrictions for HGVs when cracks as appeared.
2. 'Future-proof designs' and 'Update operating procedures' strategies: a combination of Upgrading, Prevention and Monitoring and prediction policies of Table 44. The upgrading policy implies replacement of the damaged upper layers as part of regular maintenance works. The prevention policy implies changing specifications of all materials for new construction and maintenance or installs artificial cooling or heating.
3. 'Monitoring' strategy: this strategy will build up a knowledge base of deterioration models and the impacts of site factors, allowing better informed decisions for maintenance and upgrading. The monitoring may also include the socio-economic impacts of implementing or not implementing adaptation measures. This strategy thus serves the decision making between strategies, and the selection of measures in a strategy.
4. 'Research' strategy: this strategy aims at improving the measures implemented in the first two strategies with respect to cost-effectiveness, traffic hindrance, road user safety or network operation. The research may include materials and construction methods, early warning systems and socio-economic models.

At present, most NRAs adopt the 'Do minimum' strategy, and some NRAs have started adapting their material specifications as part of the 'Future-proof designs' strategy (CEDR, [2]).

The decision to adopt a strategy or shift from one strategy to another can be based on the following considerations:

- The Monitoring strategy is a no-regret option that facilitates further decision making.
- The impact of higher temperatures on pavements will depend on poorly known site specific factors, uncertainty in climate change projections and socio-economic developments. All decisions should therefore be based on impact studies considering all these factors.

- In the ‘Do minimum’ strategy, cost-benefit studies (including socio-economic cost) will support decisions between corrective maintenance and traffic management strategies imposing access restrictions for HGVs.
- For upgrading existing roads for an additional service life of 10-20 years, cost-benefit studies will help decide between maintaining current material specifications and applying materials that are more resilient to higher temperatures, i.e. a change to the ‘Future-proof designs’ strategy.
- For new construction of roads with service lives of 30-50 years, cost-benefit studies can support the decision to change to the ‘Future-proof designs’ strategy. Cost-benefit studies need to consider uncertainty explicitly, both in climate change and in traffic volume. The latter is probably most influential.
- Cost-benefit studies for specific innovative measures can be initiated as part of the ‘Research’ strategy, to demonstrate the potential of measures aimed at reducing pavement temperature (P2R2C2 [11]).

4.3.9 Step 8: Stakeholders to be involved

The main stakeholder is the NRA. Funding agencies need to be aware of the additional cost for adaptation, and the impacts of the ‘Do minimum’ strategy.

4.3.10 Step 9: Existing knowledge gaps

Measures in the Research category of the database are:

- Preventive information: early warning, monitoring and prediction systems for construction integrity.
- Real time weather and traffic forecast

4.3.11 Step 10: Time to market of upcoming techniques

The technology readiness level (TRL) of the measures is estimated as:

- Preventive information : early warning, monitoring and prediction systems for construction integrity – TRL 6: prototype demonstrated in relevant environment.
- Real time weather and traffic models – TRL 8: system completed through test and demonstration

The FEHRL Resilient Road roadmap [3] estimates the following times to market:

- Preventive information : early warning, monitoring and prediction systems for construction integrity – R&D 5 years, demonstration 5 years; regulatory framework 3 years; time to market 2012-2025 (13 years).
- Real time weather and traffic models – R&D 5 years, demonstration 5 years; time to market 2012-2022 (10 years)

5 Traffic management in situations with operation restrictions

5.1 Introduction

Whatever the consequences of climate change (long term deterioration, extreme event …), this has impact on the services offered to the user. Traffic management solutions may alleviate the diminution of the service. That's why traffic management measures appear as one of the technique in the tables concerning the vulnerability of the various assets (chapters 2 to 4). Here, the idea is to consider "mobility services" as the asset.

5.2 Mobility Services during extreme weather

5.2.1 Step 0: The road owner's needs

Until recently road administrations main goal was building and maintaining a road network. Of late, there has been a transition from this traditional approach to an operation function that includes a policy oriented towards the user. This is what is called the "big shift" in the road network operation handbook edited by PIARC [34].

Also as stated in the main conclusions of the CEDR report 'Traffic Management to reduce congestion' [35]:

> "Traffic management is a relatively new part of most national traffic and transport policies. Some highly populated countries with dense motorway networks and high congestion levels have made a shift in policy from reflexive road extension to a concept of better utilisation of the existing network that includes traffic management. Other European countries have not yet encountered such problems and are not at the same level of deployment of traffic management measures. Besides this, some countries have more urgent traffic problems than congestion and give priority to weather-related problems such as snow and ice. This means that there are significant differences in the amount and type of measures in the field of traffic management and control".

Distinction between event affecting the concrete road itself or not
We can distinguish two types of threats where traffic management measures are at stakes according to the type of weather events and their effect on the road:

- When a threat affects the road itself (pavement, structure, etc.). Then, the traffic management measures that can be taken have already been mentioned in previous chapters.
- When the road is not affected by itself, but only the traffic service is affected, that is to say there is no consequence for the road itself, but the ability to drive is reduced, or the speed is limited for example.

Of course, all the threats (of first type) can bring into play any traffic management measures. And there is no use of re-listing them here again. However, it is necessary to address the threats of this second type.

We will then mainly focus on the threat Loss of driving ability due to extreme weather events, and its sub-threats:

- Reduced visibility (fog)
- Reduced vehicle control (snow or heavy rain)
- Decrease in skid resistance on pavements from slight rain after a dry period
- Icing and snow

5.2.2 Step 1: Definition of the relevant climate variable from design guidelines

Table 45 gives the climate parameters for the threat Loss of driving ability due to extreme weather events, and characterises it in terms of unit and time resolution.

Regarding specifically the snowfall and icing threats:

- In temperate climate countries, the average elevation of temperature should theoretically improve the situation, but :
    - The number of days with zero °c crossing may increase
    - In Northern countries, de-icing of permafrost may lead to structural disorders and landslide (also for mountainous areas in middle/South Europe) :
    - White road/ black road strategies
- Additionally, number of precipitations (snow) may decrease, but their intensity may increase in southern Europe.
- Moreover, because of strong winds during winter period, the risk of snowdrifts may increase.

The CEDR report on climate change states that more intense precipitation will result in more frequent or intensified snowfall in high-latitude or mountainous regions, with an impact on demand for snow ploughing. More wind in these regions will increase snow drifting and thus necessitate more ploughing. In the lowlands, less snowfall is expected, since a greater proportion of the winter precipitation will be rain.

Table 45: Climate parameters for the Loss of driving ability due to extreme weather events

Threat description	Climate information			Vulnerability factors	Impact	
Specific threat	**Climate parameter (an increase of the mentioned variable will increase the possibility of the threat happening)**	**Unit**	**Time resolu-tion for climate variable**	**Infrastructure intrinsic factors = road factors that contribute to vulnerability**	**Duration of the threat when it has occurred until resume of normal operation**	**Time between realization that threat might happen and threat occurring (warning time horizon)**
Reduced visibility	Fog days	Number of days	day		hours – day	seconds – minutes
Reduced visibility during snowfall, heavy rain including splash and spray	Snowfall or rainfall	mm/hour and mm/day	hour-day	Closed pavements (no porous pavements), presence of storm water runoff	minutes – day	seconds – minutes
Reduced vehicle control	Extreme wind speed (worst gales and wind gusts)	m/second	Wind gust		hours – day	seconds
Decrease in skid resistance on pavements from slight rain after a dry period	Drought (consecutive dry days)	consecutive days	multiple days-months	Pavements	minutes – hours	seconds – hours
Flooding of road surface due to low capacity of storm water runoff (see also chapter 2.2)	Extreme rainfall events (heavy showers)	mm/hour	minutes – hour	Closed pavements (no porous pavements), presence of storm water runoff	minutes – hours	minutes
Aquaplaning in ruts due to precipitation on the road, splash and spray	Extreme rainfall events (heavy showers)	mm/hour	minutes - hour	Closed pavements (no porous pavements), presence of storm water runoff	minutes - hours	minutes
Decrease in skid resistance on pavements from migration of liquid bitumen (see also chapter 4.1)	Maximum and minimum diurnal temperature and number of consecutive hot days (heat waves)	˚C and number of (consecutive) days	days	Asphalt pavements	hours - days	minutes
Icing and snow	Snowfall	mm/day	days		hours - days	seconds - hours
	Frost and rainfall	˚C and number of days	days			

5.2.3 Step 2: Resilience of the asset in current situation

Concerning the threats that have an impact on skid resistance (icing, snow, heavy rainfall, slight rain after a dry period), the resilience of the road is mainly a matter of pavement. This point is treated in previous part of the report.

The considered asset here is the mobility service, in other word, the fact that the road offers its best service to the traffic. This includes the road in a broad sense, with its accompanying systems such as information, safety, gas stations, etc.

The resilience of the asset is its ability to recover when an event occurs. In the case of the road, the primary mission is to ensure that the traffic is able to go from one point to another. When a road is affected by an event, it is resilient if it is able not to close entirely in order to ensure its basic mission, as for example in the following cases (in decreasing order of level of service):

- only one or some lanes are closed, and with a sufficient number of lanes that are still open with a sufficient capacity for the traffic demand,
- one of the two sides of a motorway is closed, but a cross-over is put into place that allows traffic to go through in both direction,
- the road is closed in one or two ways on short section, and concerned traffic is properly diverted/assigned and guided on alternative road(s), so that traffic can globally still go on.

The main factors affecting the resilience of the road are (ordered in decreasing importance):

- The number of lanes. In particular, the fact that it has at least two lanes per direction and an emergency lane. (Note that it is the case for the large majority of the Trans-European road network).
- Its ability of putting into place carriageway cross-over (traffic goes through central reservation if any, and one of the two sides of the road become bi-directional while the other side is closed).
- The existence of traffic management plan and information systems: VMS (Variable Message Systems), Radio, and other communication networks.

For the first two characteristics, the resilience analysis of the road should be done stretch by stretch (between interchanges or exit/access nodes); and at regional/national level for the last one.

'ITS are more vulnerable than concrete roads', life expectance is usually shorter than the road itself, electronic equipment have short life expectancies.

When planning the development of ITS systems dedicated to traffic management measures in general, it is therefore important to ensure the resilience of the road equipment, particularly on the most vulnerable stretches of the network.

5.2.4 Step 3: Resilience of the asset in possible future situations

It is difficult to assess the resilience of mobility services in the future. Mobility services can be impacted either by the impact on infrastructure of climate change parameters (see former sections) either by extreme weather events that don't impact the infrastructure.

The evolution of the frequency and strength of weather events is difficult to predict (see part A of the ROADAPT guideline, [39]) and the relation with climate change not straightforward.

Elevation of temperature may lead for example to less snow falls in the North of Europe, while heavy rain episodes become more frequently with the increase of flood risk.

In the meantime, the population awareness to these events, the influence it may have on public authorities, the development of new technologies, will lead to improve the resilience of the mobility services (e.g. by the development of contingency plans, public information).

Finally, our assumption is that in the future, the resilience of the asset 'mobility services' is similar to that of the present situation.

5.2.5 Step 4: Identification of applicable / appropriate adaptation measures

Traffic Management measures are not specific to extreme event management. Their main objective is generally to ensure safety and also to reduce congestion. Since the traffic management system is not devoted to only one goal, it seems useful to present an overview of traffic management measures, not only those related to climate change and/or extreme event management.

The following table is extracted from in the CEDR report Traffic Management to reduce congestion [35].

Table 46: Definition of traffic management measures to reduce congestion, by type of intervention

Intervention	Goal	Traffic management measure
Flow control	To harmonise traffic	**Speed control / limits**
		HGV overtaking ban
		Incident warning
Capacity control	To increase throughput on road sections	Hard shoulder running
		Dynamic lane management
Network control	To reduce inflow, maximize outflow, re-route traffic	**Re-routing**
		Ramp metering (access restriction)
		Interchange lane control
Traffic information	Information on travel time, congestion, incidents, weather, etc.	**Traffic and travel time information**
		Incident management
		Co-modal traveller information

The measures in **bold** are useful to adapt to climate change and/or for extreme event management.

First of all, we should note that Real time weather and traffic forecasts, preventive information, real time traffic info, modal shift, are parts of all traffic management adaptation measures.

Table 47 gives the list of all measures that can be implemented as a response to an extreme event. It also defines which measure can be used for the following threats (that are specific to traffic management):

- Reduced visibility (fog).
- Reduced vehicle control (snow or heavy rain).
- Decrease in skid resistance on pavements from slight rain after a dry period.
- Icing and snow.

Table 47: Traffic Management measures

Nr.	Role of measure	Adaptation measure	Stage	Scale	Measure used for the following threats (Y/N)			
					Reduced visibility (fog)	Reduced vehicle control (snow or heavy rain)	Decrease in skid resistance on pavements from slight rain after a dry period	Icing and snow
1	All categories	Prepare Traffic Management Plans	Prevention	TEN-T - national - regional	Y	Y	Y	Y
2	Information / Warning	Placing warning signs	Preparation - Prevention	Object Stretch - network	Y	Y	N	Y
3		Modal shift	Prevention - Response	Regional network	Y/N	Y/N	N	Y
4		Real time traffic information	Prevention - Response	Object - stretch - network	Y	Y	Y	Y
5	Access restriction	Ramp Access restriction	Response	Stretch - network	N	Y/N	N	Y
6		Weight limits	Prevention - Response	Stretch	N	Y/N	N	Y
7		HGV Storage	Prevention - Response	Stretch	N	Y/N	N	Y
8	Reducing mobility service	Lane closure	Response	Stretch	N	Y	N	Y
9		Rerouting and guidance	Prevention - Response	TEN-T - national - regional	N	Y	N	Y
10		Speed limits	Prevention - Response	Stretch	Y	Y	Y	Y

5.2.6 *Step 5: Establishing a policy*

In order to implement traffic management measures, the road network first needs to have a management plan. Many measures can also be implemented only if a specific traffic management system has been implemented, e.g. information to user if VMS systems has been installed.

When such traffic management plans already exist, all possible strategies of traffic management measures are specified in it. It greatly depends on the systems that are operating.

In the ROADAPT policy matrix below, traffic management is a category of adaptation measure.

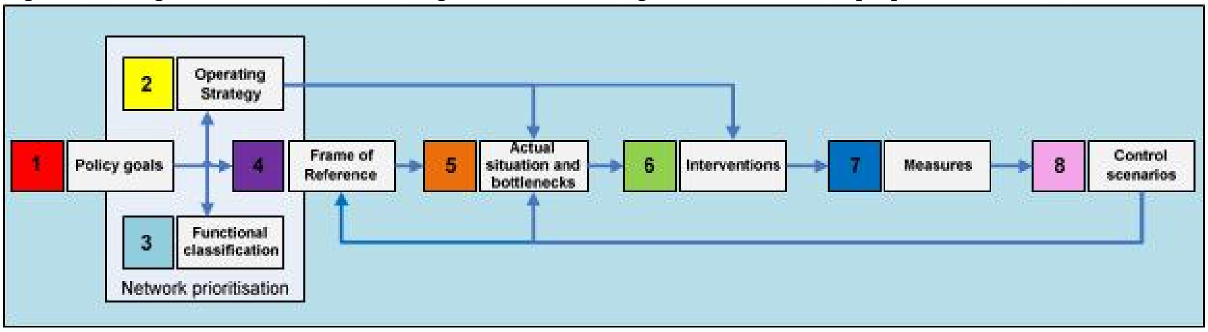
Figure 2: Policy matrix

STAGES	PRO-ACTION	PREVENTION	PREPARATION		RESPONSE		RECOVERY
			In preparation of an extreme event	Just before an extreme event	During an extreme event	Just after an extreme event	After an extreme event
OBJECTIVES	*Enable smooth and safe traffic*		*Support disaster consequence reduction*	*Evacuation route, life supply route*	*Minimizing loss of functions*	*Supply route for repairs and humanitarian aid*	*Supply route for recovery of affected area*
Planning for CCI&EWE	**Pro-active attitude**			**Extreme event management**			
Robust construction		**Prevention**					
Legislation , regulations							
Resilient construction		**Upgrade, retrofit, new construction**					
Maintenance and management			**Preventive Maintenance and Replacement**				**Corrective Maintenance and Replacement**
Traffic management for CCI&EWE		**Traffic management**					
Capacity building	**Capacity building**						
Monitoring	**Monitoring and prediction**						
Research	**Research**						

All the traffic management measure will then fall here into the traffic management category and/or the extreme event management (which spread from stage prevention to stage recovery), so there is no added value of presenting the matrices for these measures.

However, what is interesting is how the choice is made to select measures (that are mixed into strategies). The CEDR report 'Traffic Management to reduce congestion' [35] proposes an 8 step approach for selecting traffic management measures, see Figure 3. This methodology can be used in fact for any situation where the traffic flow is hampered.

Figure 3: Diagram for decision making for traffic management measures [35].



According to the CEDR report, steps 1, 2, and 3 are the basis for decision-making in traffic management. These exercises only have to be done once and refer to the transport policy and strategies defined by the NRA.

The objective of step 4, frame of reference is to determine how the traffic problems will be quantified (e.g. delays, time loss, safety risks, GHG emissions) in order to prioritize the difficulties.

In step 5, locations and difficulties are listed while step 6 identifies what is termed ’interventions’. These are not yet measures, but sort of traffic strategies such as the following concerning traffic congestion:

- Flow control: to harmonise traffic.
- Capacity control: to increase throughput on road sections.
- Network control: to reduce inflow, maximize outflow, re-route traffic.
- Traffic information: travel time, congestion, incidents, weather, etc.

Detailed traffic management measures are defined in step 7. Step 8 includes the monitoring of the measures and feedback.

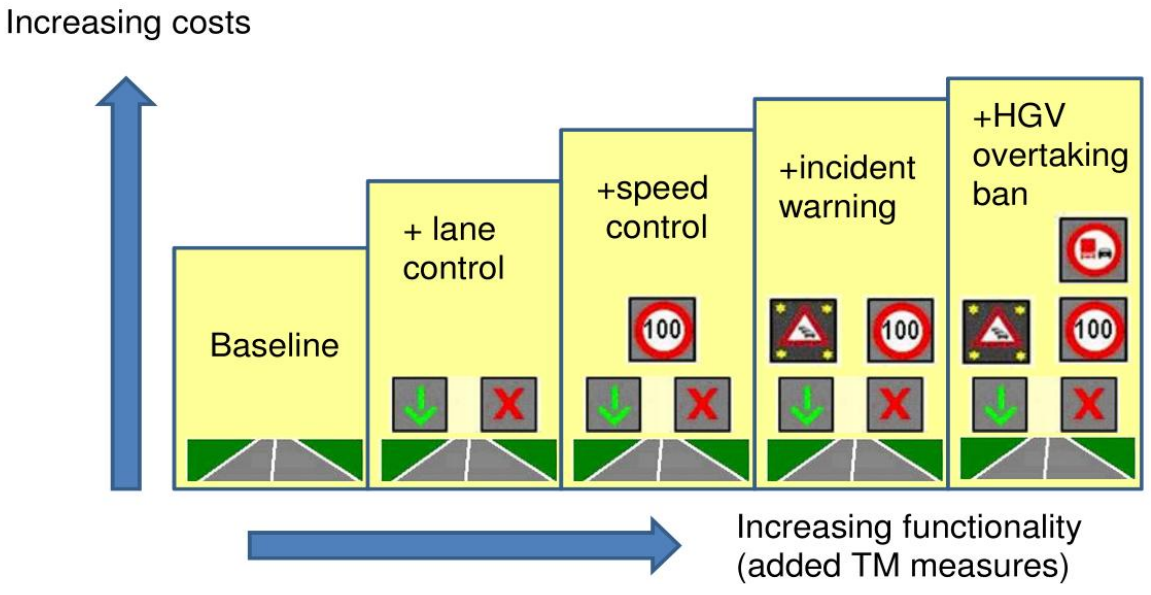
5.2.7 Step 6: Assessment of consequence criteria for measures

The following table is extracted from the ROADAPT database of adaptation measures. It listed all traffic management measures, whatever the threats.

An assessment of the consequences of the measures is given in Table 70 in Annex C. The rating of the measures depends also on the importance of the road and the traffic flows that use it.

For direct cost, the reader can find very useful information in the CEDR report ‘Traffic Management to reduce congestion’ [35]. Extracted from this report, the next figure shows how traffic management measures can be mixed and the related marginal costs.

Figure 4: Costs of traffic management with shared functions [35].



5.2.8 Step 7: Decision on the most appropriate strategy and shift from one strategy to another

In order to alleviate the impact of Climate Change on Mobility services, Traffic management strategies are complementary to “hard measures” (road infrastructure design and maintenance) that are developed in the preceding sections.

There are some exceptions where, considering the current state of the art, there is no technique available except traffic management strategies in case of reduction or loss of driving abilities due to some extreme weather events: heavy rain, strong wind, heavy snowfall, black ice, intense fog.

Therefore, we can consider that traffic management strategies should be implemented in all circumstances that lead to a diminution of the level of the Mobility Services.

On the operation side, traffic management measures use to be classified in 3 levels:

- **Information/warning** of the road users (e.g. “warning, poor visibility between A and B on highway M)
- **Recommendations** to the road user (e.g. “warning, poor visibility between A and B on highway M, reduce speed)
- **Obligation** (e.g. “warning, poor visibility between A and B on highway M, speed limited to 50 km/h)

The shift from one level to another is defined by operation procedures according to the events in real time. According to the importance of the event, traffic management measures have to be adapted regarding the stakes, going from an information level to an obligation level.

The decision to adopt an operational strategy or shift from one to another is not relevant for the traffic management measures: they have to be implemented every time when the level of service is decreasing. Real time traffic models (that give socio-economic impacts) can be used in order to evaluate the impacts of traffic management measure, and choose the optimal operational strategy.

As for the other assets (e.g. the traffic management system as a whole), the following overall strategies can be identified in the traffic management measures for adaptation:

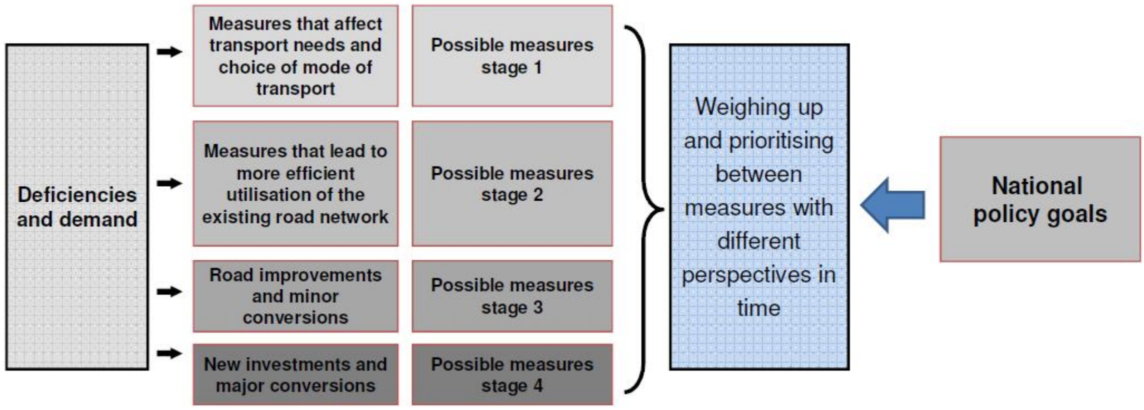
1. 'Do minimum' strategy, correspond to the road operating strategy, which is a combination of the maintenance/management (Preventive and corrective maintenance and replacement), and Traffic management in the case of extreme event. The 'Traffic management' policy consists in that case in:
   - Informing users on the situation
   - If necessary, limit access or close access with on the ground classical equipment (traffic signs, traffic cones, barriers, etc.)
2. 'Future-proof designs' strategy: a combination of 'Upgrade, retrofit and new construction' and 'Prevention' policies
   In terms of traffic management, the 'Prevention' policy implies to prepare traffic management plans. The EASYWAY program has defined guidelines for setting up Traffic Management plans [36]. Traffic Management plans are established according to the characterization of the situations, thanks to various pre-established criteria.
   They may require for certain measures to be supported by regulatory measures (e.g. ban of certain vehicles categories, storage of trucks on safe area, etc.).
3. 'Update operating procedures' strategy: a combination of 'Pro-active attitude', 'Monitoring and prediction' and 'Extreme event management' policies.
   The 'Pro-active attitude' policy implies the preparation of contingency plans and the collection of relevant data. The 'Monitoring and prediction strategy' will provide data for real-time analysis and prediction of the probability of an event, allowing emergency measures to be taken.
   This strategy focusses on anticipating the phenomena and to be prepared for implementing the Traffic Management plans, thanks to forecast on:
   - The weather situation
   - The traffic

   Time horizons for forecast can be from several days to some hours.
4. 'Monitoring strategy": in terms of traffic management, this strategy will build up a knowledge base of traffic models able to support better informed decisions for establishing the traffic management plans. The monitoring may also include survey of users and/or socio-economic impacts assessment of implementing or not implementing adaptation measures. This strategy thus serves the decision making between strategies, and the selection of measures in a strategy.
5. 'Research' strategy: this strategy aims at improving the measures implemented in the 'Future proof designs' and 'Update operating procedures' with respect to cost-effectiveness and network operation. The research may include non-destructive monitoring methods, early warning systems and socio-economic models.

In order to shift from strategy to another (in other words, should a traffic management system be put into place), the best solution is to undertake cost-benefit studies.

The CEDR report on traffic management to reduce congestion [35] presents a 'four stage approach' that has been developed by Finland and Sweden. It is also relevant for traffic management system for adaptation to climate change.

Figure 5: Four stage approach for adaptation of traffic management to climate change [34].



5.2.9 Step 8: Stakeholders to be involved

The main stakeholder is the NRA and road operators. Funding agencies need to be aware of the additional cost for adaptation, and the impacts of the 'Do minimum' strategy.

The other stakeholders to be involved are:
- Meteorological institutions: climate change forecast and weather forecast
- Police (enforcement of specific regulation, e.g. HGV storage)
- Assistance services (tow vehicle in case of breakdown) and rescue service (emergency vehicles in case of accident)
- Media (Radio, TV, e.g. for traffic information)
- And more and more, every citizen (social networks)

5.2.10 Step 9: Existing knowledge gaps

Implementing efficient traffic management strategies requires an accurate and timely knowledge of the traffic situation and its probable evolution.

Progress has been made in recent years for implementing cost effective traffic data collection. The emergence of floating car data technologies today and more generally of the connected car tomorrow offer new facilities for the traffic managers. Traffic forecast (short term, medium term) are also available, but mainly based on models using traffic counts collected with classical techniques (mostly traffic loops in Europe).

Assessment of the weather situation on the road is also today more accurate and reliable. Weather forecast methods have also made progress. On the other hand:
- News forecast methodologies and tools using the data collected by the users are not enough developed.
- Models combining traffic data and weather data are not yet in the operational phase.

If we consider now extreme weather events, there is really no cost effective means to alleviate, counterbalance them:
- Heating pavements are costly and can only be used on limited stretches.
- Fog dissipation techniques have been experimented on airports, but attempts to transfer this technology for roads have not been successful…

In summary, we are forced to continue, for years, to live with these extreme events and adapt the road and the traffic to them.

5.2.11 Step 10: Time to market of upcoming techniques

The connected vehicle
The main evolution to come in the domain of mobility services and traffic management is certainly that of the connected vehicle. Today, vehicles are already connected with the infrastructure thanks to the navigation systems (receiving info via RDS/TMC, or other telecom networks). Some of them are also contributing to the data collection by sending to their information service provider's information on their location and speed.

In the future, vehicles will be connected through a dedicated communication link based on short range communication (5,9 GHz), that will allow as well connection between vehicles themselves and be able to support safety oriented applications.

A lot of activities are underway in Europe and other part of the world in order to support the deployment of the communication systems and the associated services. The main difficulties are economic:

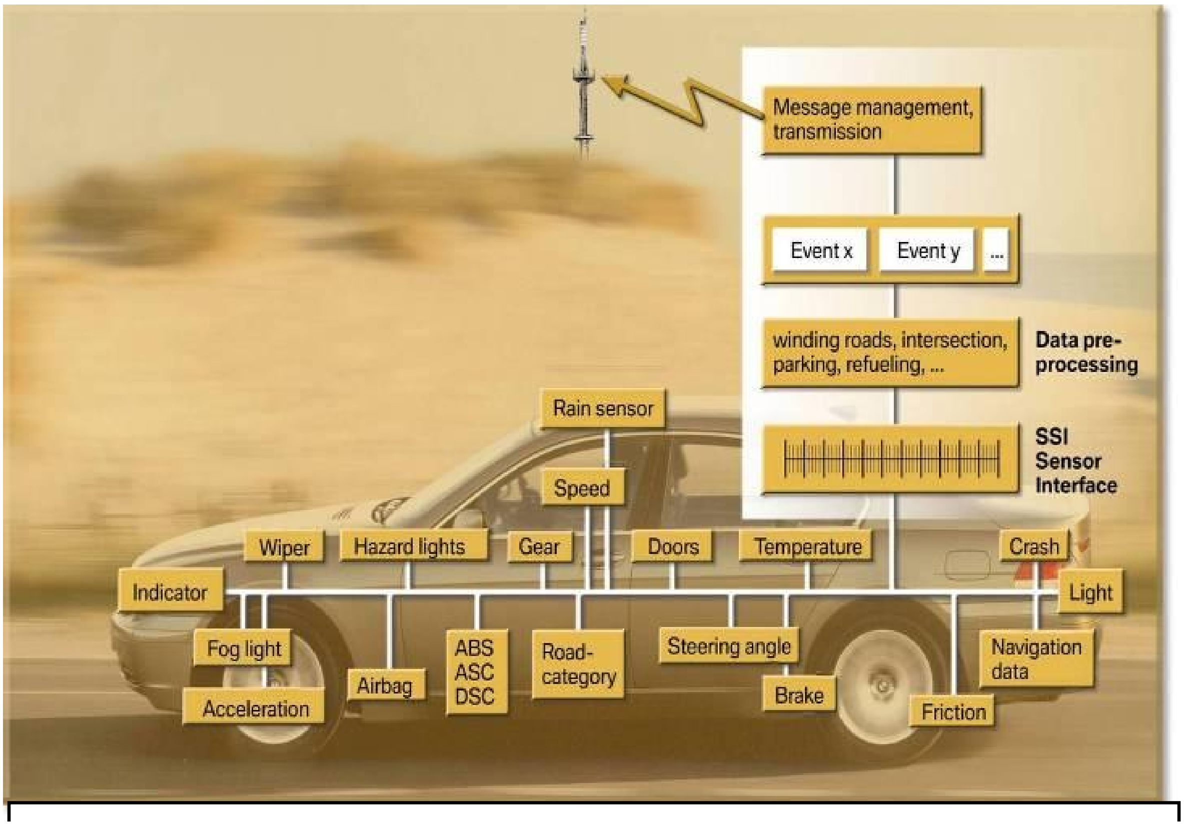
- The business models are involving public and private partners
- There are potentially important social benefits in terms of safety improvement, congestion alleviation; environmental impacts reduction provided a sufficient number of vehicles are equipped.
- Vehicles will be equipped, if car buyers are ready to pay for individual services that could be implemented. And services will be developed only if there is a significant market and therefore a communication infrastructure that neither NRAs, nor private operators are ready to finance today.
- In addition, vehicle to vehicle communication will benefit only when a significant part of vehicles are equipped.

A report common to PIARC and FISITA has been issued in 2012 by these organisations. The report [37] details these difficulties and makes some recommendations.

If we look now at the different techniques that are of interest for our purpose, connected vehicles open the way for a lot of improvements for managing traffic in weather adverse conditions.

Figure 6 (extracted from the PIARC/FISITA report) gives an idea of all data concerning a vehicle and that could be exploited by various connected vehicle applications and services.

Figure 6: The intelligent car (Source: BMW).



Among these applications and services, techniques are at different TRLs (Technology Readiness Levels):

- Traffic data collection domain (position, speed, etc.): TRL 9. However, techniques for exploitation of these data in order to improve the current traffic forecast tools are still at the TRL 4-5.
- Weather data collection based on the vehicle: fog lights on, wipers in action, rain sensors, friction sensors, temperature, etc.: these data are already exploited inside the car, but are not transmitted yet. TRL 5-6
- Integrated forecast models taking into account traffic and weather forecast: TRL 2-3. The objective is to reach TRL 5 to 7 in the Infravation program.

Other development on vehicles

Other techniques for improving driving conditions under bad weather conditions are under development by the automotive industry. They are not really in the scope of NRA, but deserve to be quoted:

- All autonomous devices, systems based on a better control of skid resistance, trajectory, in critical situation (ABS, ESP, …) TRL 9
- Devices keeping trucks from jack-knifing (trucks jack-knifing are a major concern for road operators, as they can block the traffic and even hinder the snow-clearance services…resulting in a full blockage of road.

Data collection and surveillance

Concerning data collection and surveillance, many techniques are under development with the permanent objective of cost efficiency and sustainability. :

- Non-intrusive equipment such as video camera, infra-red detectors, already on the market

- Use of Bluetooth stations able to “listen” to the mobile phone ID and used for travel time calculation (and therefore able to detect abnormal travel times due to incident). Already in operation (TRL9)
- Use of drones in order to better monitor large incidents, especially when the location is not easily reachable by the road (many vehicles blocked, snow drifts, etc…). Drones cannot be deployed in case of heavy snowfall or strong wind: TRL 8

Research on infrastructure
Concerning infrastructure, research and pilot projects are underway concerning:

- Heating pavement: techniques are existing or/and under development, but the cost of the current solutions does not allow a generalisation. TRL 7
- Fog clearance systems, same observation. TRL 7

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Annex A: Criteria and rating of performance of the adaptation measures

The criteria and the rating are derived from the risk evaluation study for the Netherlands highway network [32].

The reference for assessment of the adaptation measures is the present climate and the present practice of road construction and operation, but assuming that the road is vulnerable in the present climate as well. The assessment of the measure is found by answering the question ‘What will be the impact if the NRA will implement this measure today?’

An explanation of the scores is given below.

Availability
Definition: impact of the measure on the motorway availability, in terms of traffic restriction or interruption.

Scores for assessing the measures in the database:
-3 A catastrophic impact on the availability
-2 A serious impact on the availability
-1 A minimal negative impact on the availability
0 A negligible impact on the availability
+1 A minimal positive impact on the availability
+2 A large positive impact on availability
+3 A very large positive impact on availability

Safety
Definition: impact of the measure on the motorway user safety, from light material damage to casualties.

Scores for assessing the measures in the database:
-3 A catastrophic influence on user safety, with as a consequence deadly danger during normal use (serious material damage, heavy injuries, casualties)
-2 An influence to such extent that the boundaries of user safety are exceeded, with as a consequence a serious increase of the number of accidents with permanent loss of health (serious material damage, heavy injuries)
-1 An influence that reaches the boundaries of acceptable user safety, with as a consequence a number of accidents with temporary loss of health or injuries without absence (material damage, slight injuries)
0 A negligible impact on the user safety (light material damage), but within acceptable limits
+1 An influence that causes a reduction of the number of accidents with temporary loss of health or injuries without absence (material damage, slight injuries)
+2 An influence that causes a serious decrease of the number of accidents with permanent loss of health (serious material damage, heavy injuries)
+3 An influence that substantially reduces deadly danger during normal use (serious material damage, heavy injuries, casualties)

Surroundings (effects on the surrounding road network)
Definition: impact of a traffic interruption occurring on the motorway due to the implementation of the measure, over the surrounding road network, in terms of affected road length.

Scores for assessing the measures in the database:

-3	A catastrophic impact on the use of the nationwide network, the road network is at stake
-2	A serious impact on the use of the regional network, a road stretch is at stake
-1	A minimal negative impact on the use of the regional network, a road section is at stake
0	A negligible impact on the use of the local network, a road segment is at stake
+1	A minimal positive impact on the use of the regional network, a road section is no longer vulnerable
+2	A large positive impact on the use of the regional network, a road stretch is no longer vulnerable
+3	A very large impact on the use of the nationwide network, the road network is no longer vulnerable

Direct technical costs
Definition: direct technical costs for implementing the measure, incurred by the motorway operator. These are total costs of ownership i.e. costs for construction and replacement, maintenance, traffic and incident management and repair of damage. Cost for the road user or society are not included.
An increase in cost for implementing the measure may be compensated by a decrease in cost for maintenance, repair or incident management. Thus, the net total cost for implementing the measure may be negligible or even positive (cost saving).

The reference for the costs or savings is the current practice in the current climate. For measures that are:

- An addition to the current practice, e.g. raising a road above flood level: consider additional costs or savings
- A change in the current practice, e.g. revised standards for road design: consider only incremental costs or savings as compared to current practice
- A continuation of current practice, e.g. deployment of de-icing agents: no additional costs or savings

For comparison of costs and savings of different types of measures, costs and savings should be expressed as the average annual costs or savings for a road stretch of 20 km length, for a reference period of 50 years:

- Measures that are permanent, costs or savings occur one time only, e.g. raising a road above flood level: estimate the one-time costs or savings, divide by length of reference period
- Measures that are permanent, costs or savings occur once in the service life of the road (once per 20-30 years), e.g. revised standards for road design: estimate the one-time costs or savings, divide by length of service life
- Measures that are permanent, costs or savings occur yearly, e.g. keeping records of flooding events and locations: estimate average yearly costs or savings
- Measures that are incidental, cost or savings depend on frequency of extreme weather events, e.g. access restrictions after flooding: estimate costs or savings per event, divided by the estimated return period

Scores for assessing the measures in the database:
-3 More than k€ 500 costs for implementing the measure
-2 Between k€ 100 and k€ 500 for implementing the measure
-1 Between k€ 25 and k€ 100 costs for implementing the measure
0 Between k€ 25 costs and k€ 25 savings for implementing the measure
+1 Between k€ 25 and k€ 100 savings from implementing the measure
+2 Between k€ 100 and k€ 500 savings from implementing the measure
+3 More than k€ 500 savings from implementing the measure

Reputation
Definition: dissatisfaction with and loss of reputation of the motorway operator because of inadequate actions to prepare for and manage extreme weather events.

Scores for assessing the measures in the database:
-3 Extreme loss of reputation (due to completely inadequate preparedness or acting), position of minister at stake
-2 Substantial loss of reputation (due to inadequate preparedness or actions on a large amount of aspects), reputation has a set-back, notices in media with attention to physical damage / hardships of road users, gets attention in nationwide politics
-1 Slight to moderate loss of reputation (due to inadequate preparedness or actions on some aspects), notices in media with attention to (fictive) loss for road users
0 No significant impact on reputation (due to proper actions); no complaints
+1 Slight improvement of reputation; positive media attention for adequate actions or preparedness
+2 Substantial improvement of reputation; increased acceptance of delays with road users; positive scores for availability and safety in road user panels; gets attention in nationwide politics
+3 . . .

Annex B: Criteria and rating of sustainability of the adaptation measures

Sustainability criteria

Many systems exist for assessing sustainability of road infrastructure. The project SUNRA lists 16 systems [19] All systems use a limited number of sustainability criteria for which a score is to be determined. Many criteria are common between the systems. The following criteria were derived specifically dfrom the assessment systems BREEAM INFRA [20], SUNRA [21] and US Green Roads [22]:

Climate change and Energy
People and Communities
Ecology / Biodiversity
Physical resources
Quality of Life
Safety. Health & Equity
General / management

What do the criteria cover

Below a list is given of examples of metrics for each sustainability criterion.

General / management
Corporate Social Responsibility in the chain
Reporting and accountability (open, transparent, environmental)
Adaptive capacity (= future-proof design)
Participation
Site and environment
Performance Assurance
Contract chain partners
Contract Formation
Robust design
Connection to public transport
Environmental Review Process – Complete a comprehensive environmental review
Lifecycle Cost Analysis (LCCA) – Perform LCCA for pavement section
Lifecycle Inventory (LCI) – Perform LCI of pavement section
Quality Control Plan – Have a formal contractor quality control plan
Noise Mitigation Plan – Have a construction noise mitigation plan
Waste Management Plan – Have a plan to divert C&D waste from landfill
Pollution Prevention Plan – Have a TESC/SWPPP
Low Impact Development (LID) – Complete a LID feasibility study
Pavement Management System – Have a pavement management system
Site Maintenance Plan – Have a roadside maintenance plan
Educational Outreach – Publicize sustainability information for project
Environmental Management System – ISO 14001 certification for general contractor
Quality Management System – ISO 9001 certification for general contractor
Contractor Warranty – Warranty on the constructed pavement

Climate change / energy
CO2 reduction construction
Energy-saving equipment

Application and generation of renewable energy
Illumination
Traffic flow
Reduce rolling resistance
Climate Change mitigation /adaptation
Traffic Emissions Reduction – Reduce emissions with quantifiable methods
Fossil Fuel Reduction – Use alternative fuels in construction equipment
Equipment Emissions Reduction – Meet EPA Tier 4 standards for non□road equip.
Paving Emissions Reduction – Use pavers that meet NIOSH requirements
Energy Efficiency – Improve energy efficiency of operational systems

People and communities
Aesthetics / 'environmental perception' / 'experience in use'
Social safety bicycle and pedestrian paths
Social return on investment
Education / Knowledge of / by the project
Cultural Heritage / Archaeology
Cultural heritage/visual intrusion
Affordability
Economic viability
Accessibility as a social function
Social Cohesion
Diversity
Pedestrian Access – Provide / improve pedestrian accessibility
Bicycle Access – Provide/improve bicycle accessibility
Transit Access – Provide/improve transit accessibility
Scenic Views – Provide views of scenery or vistas
Cultural Outreach – Promote art/culture/community values

Ecology / biodiversity
Water in the light of climate change adaptation
Maintaining water table
Minimize pollution runoff rainwater
Soil
Soil quality
Underground space (cables and pipelines)
Land use
Space
Integration
Abiotic structures
Natural biotic (living nature)
Sustainable landscape (roadside) management
Winter maintenance, sand / salt
Soil and water pollution
Habitat fragmentation
Invasive species due to transport
Runoff Flow Control – Reduce runoff quantity
Runoff Quality – Treat stormwater to a higher level of quality
Stormwater Cost Analysis 1 Conduct an LCCA for stormwater elements
Site Vegetation – Use native low/no water vegetation
Habitat Restoration – Restore habitat beyond what is required
Ecological Connectivity – Connect habitat across roadways
Light Pollution – Discourage light pollution

Environmental Training – Provide environmental training
Water Tracking – Develop data on water use in construction

Physical resources
Building materials
Recycled Materials
Informed source materials
Land take
Non-renewable resources
Waste
Site Recycling Plan – Have a plan to divert waste from landfill
Life Cycle Assessment (LCA) – Conduct a detailed LCA of the entire project
Pavement Reuse – Reuse existing pavement sections
Earthwork Balance 1 Use native soil rather than import fill
Recycled Materials – Use recycled materials for new pavement
Regional Materials – Use regional materials to reduce transportation
Long□Life Pavement – Design pavements for long□life
Permeable Pavement – Use permeable pavement as a LID technique
Warm Mix Asphalt (WMA) – Use WMA in place of HMA
Pavement Performance Tracking – Relate construction to performance data

Quality of life
Air quality
Vibrations
Light Pollution (Construction & Use)
Heat stress (Urban Heat Island)
Noise
Traffic Flow during construction
Noise
Air pollution (humans)
Light pollution
Livability
Quiet Pavement – Use a quiet pavement to reduce noise

Health, safety & equity
Health (level: (far) below beta)
Secure infrastructure
Sustainable Yield / Total Cost of Ownership
Accessibility as an economic function
Transport operation costs
Transport facility costs
Productivity /Efficiency
Costs & benefits to the economy
Safety
Health and fitness
Security
Safety Audit – Perform roadway safety audit
Intelligent Transportation Systems (ITS) – Implement ITS solutions
Context Sensitive Solutions – Plan for context sensitive solutions
Cool Pavement – Contribute less to urban heat island effect (UHI)

Scoring

+3	= strong positive impact on the sustainability criterion
+2	= positive impact on the sustainability criterion
+1	= slight positive impact on the sustainability criterion
0	= neutral / no impact on the sustainability criterion
-1	= slight negative impact on the sustainability criterion
-2	= negative impact on the sustainability criterion
-3	= strong negative impact on the sustainability criterion

Annex C: Assessment of consequence criteria for measures

The tables in this annex refer to step 6: assessment of consequence criteria for measures, for the different threats.

Table 48: Assessment of measures for flooding of road and erosion of road embankments due to pluvial flooding and overloading of hydraulic systems crossing the road (see chapter 2.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
156	Avoid deforestation in the catchment area	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
157	Avoid urbanisation and watersheds diversions in vulnerable areas	Pro-active attitude	Object - stretch	+3	+1	0	-1	0	0	+2	-1	+3	+1	0	0
158	Build dams, reservoirs and retaining ponds to buffer the water	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0
159	Build flood walls to protect the road from flooding	Pro-active attitude	National network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
160	Carriageway cross-over	Traffic management	Stretch	-2	-1	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
161	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
162	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall	Preventive maintenance and replacement	Object - stretch	+3	+2	0	-1	+2	-2	0	+1	+1	0	0	0
163	Clear natural blockages such as shrubs and weeds	Preventive maintenance and replacement	Object	+1	0	-1	+2	-1	0	+1	0	0	+1	0	0
164	Cover road embankment with geotextile	Prevention	Object - stretch	+3	+1	0	+2	+1	+2	0	-1	-1	-1	-1	0
165	Cover slope with rock blanket	Prevention	Object - stretch	+2	+3	-1	+2	+2	+2	-1	-1	-3	-3	0	0

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Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
166	Cover slope with vegetation	Prevention	Regional network	+3	+2	+1	-2	0	+2	0	0	0	0	0	0
167	Develop plans and routines for the priority of securing areas prone to overloaded hydraulic systems	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
168	Dredge to increase depths and/or straighten the stream	Pro-active attitude	National network	+1	-1	0	-1	-1	-2	-1	+1	-2	0	0	0
169	Establish a guideline for standardized inspection of culverts	Preventive maintenance and replacement	Object - stretch - network	+3	+1	+1	-2	0	+2	0	0	0	0	0	0
170	Inspect and clean watercourses regularly	Preventive maintenance and replacement	Object	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
171	Inspect blue spots areas adjacent to heavy rainfalls	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
172	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
173	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+1	0	0	+1	-1	0	0	0	0	0	0
174	Keeping records of events and locations of overloaded hydraulic systems	Pro-active attitude	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
175	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
176	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
177	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
178	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
179	Modal shift	Extreme event management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
180	Organize weirs/overflow towards storage facilities	Pro-active attitude	Object - stretch - network	+3	+3	+2	-2	0	+2	0	0	0	0	0	0
181	Pave the inlet and the outlet of the culvert	Pro-active attitude	Object - stretch	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
182	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
183	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
184	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+1	+2	+1	+1	-1	+1	+2
185	Protect entrance embankment with rock blanket	Prevention	Object	+2	+1	0	-1	0	-1	-1	-1	-1	-1	0	0
186	Protect entrance against floating debris	Prevention	Object	+2	+1	0	-1	0	-1	-1	-1	-1	-1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
187	Real time traffic information	Traffic management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
188	Real time weather and traffic forecast	Traffic management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
189	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
190	Replace the culvert with a small bridge	Upgrade / retrofitting / new construction	Object	+2	+1	0	-2	0	-1	-1	-1	-1	-1	0	0
191	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
192	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+1	+1	-1	+1	+2
193	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
194	Reviewing design storm return periods in the light of new weather information	Monitoring and prediction	Regional network	+1	0	0	-1	+2	+1	0	0	0	0	+1	+2
195	Revised standards for design of culverts	Prevention	National network	+1	+2	0	-2	0	+2	0	0	0	+1	0	+1
196	Revised standards for road design, avoiding buildup of water level differences	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0
197	Speed limits	Traffic management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
198	Take measures to reduce downstream sedimentation and clean debris and sediment from the outlet ditch afterwards.	Prevention	Object	+2	+1	0	-2	+1	+2	-1	-1	-3	-3	0	0
199	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0

Table 49: Assessment of measures for flooding of road surface due to failure of flood defence system and inundation in coastal areas (see chapter 2.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
1	Access restriction	Extreme event management	Stretch	+2	0	-2	+2	-1	+2	+2	+1	0	+1	0	0
2	Avoid deforestation in the catchment area	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
3	Build dams, reservoirs and retaining ponds to buffer the water	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0
4	Build flood walls to protect the road from flooding	Pro-active attitude	Object - stretch - network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
5	Carriageway cross-over	Extreme event management	Stretch	-2	-1	0	-2	-2	0	0	0	0	+1	+1	+2
6	Carrying out risk assessment of identified areas	Pro-active attitude	Object - stretch - network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
7	Clear natural blockages such as shrubs and weeds	Preventive maintenance and replacement	Object	+1	0	-1	+2	-1	0	+1	0	0	+1	0	0
8	Construction of (temporary) flood barriers along road	Extreme event management	Stretch	+2	+1	+1	-2	+1	0	0	0	0	0	0	+1

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
10	Develop plans and routines for the priority of securing areas prone to flooding	Pro-active attitude	Object - stretch - network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
11	Drainage of road embankment for fast lowering of groundwater table after flood retreats	Upgrade / retrofitting / new construction	Object - stretch	+1	0	0	-1	+1	-2	-1	-1	-1	0	0	0
12	Dredge to increase depths and/or straighten the stream	Pro-active attitude	National network	+1	-1	0	-1	-1	-2	-1	+1	-2	0	0	0
13	Elevated roads above High Water Level	Prevention	Stretch - network	+2	+2	+2	-3	+1	+2	0	0	0	-2	0	+2
15	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
16	Integration of infrastructure development and land use planning	Pro-active attitude	Regional network	+2	+2	+2	+2	+1	+2	0	0	+2	+2	0	+2
17	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0
18	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
19	Lane closure	Extreme event management	Stretch	-2	+3	0	-2	-2	0	+1	-1	+1	0	-1	+2
20	Make strategies for temporary rerouting	Pro-active attitude	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
21	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
22	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
23	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
24	Prepare contingency / emergency plans	Pro-active attitude	Regional network	0	+3	+1	0	-1	+2	0	0	0	0	0	+2
25	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+2	+2	+2	0	0	+1	+2
26	Preventive information	Research	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
27	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
28	Relocation of road	Prevention	Stretch - network	+2	+2	+2	-3	+2	+2	0	0	0	0	0	+2
29	Remove large obstructions (such as fallen trees or rubbish which restrict flow	Corrective maintenance and replacement	Object	+3	+2	0	+1	+1	+1	0	+1	-1	0	0	+1
30	Remove recent accumulations of debris which create obstructions to flow	Corrective maintenance and replacement	Object	+2	+1	0	-1	+1	+2	0	0	0	0	0	0
31	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
32	Rerouting and guidance	Extreme event management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+2	0	-1	-1	+1
33	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
34	Revised standards for road design, avoiding buildup of water level differences	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0
35	Shelter locations with facilities and life supplies, evacuation routes	Prevention	Regional network	0	+3	0	-2	+2	+2	0	0	0	0	0	+2
36	Speed limits	Extreme event management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2
37	Use geosynthetics for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	0	+1	0	0
38	Use vegetation for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	+2	+1	0	0
39	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0
96	Inspect and clean drainage systems regularly	Preventive maintenance and replacement	Object	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
103	Mangroves restoration to reduce wave run-up and shore erosion	Pro-active attitude	Regional network	+1	0	0	+1	+1	-1	+2	+2	+3	+2	+1	+2
105	Physical reinforcement of the coast line to protect against wave action	Pro-active attitude	Object - stretch	+2	0	0	-2	-1	+1	0	-3	-3	-2	-1	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
116	Reviewing design storm return periods in the light of new weather information	Monitoring and prediction	Regional network	0	0	0	0	0	0	0	0	0	0	0	0
118	Sand nourishment to reduce wave run-up and shore erosion	Pro-active attitude	Regional network	+1	0	0	+2	+1	-2	-1	+1	-1	-2	0	0

Table 50: Assessment of measures for flooding of road surface due to pluvial flooding (see chapter 2.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
40	Access restriction	Extreme event management	Stretch	+2	0	-2	+2	-1	+2	+2	+1	0	+1	0	0
41	Avoid deforestation in the catchment area	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
42	Build flood walls to protect the road from flooding	Pro-active attitude	National network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
43	Build flood walls to protect the road from flooding	Pro-active attitude	National network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
44	Carriageway cross-over	Extreme event management	Stretch	-2	-1	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
45	Carriageway cross-over	Extreme event management	Stretch	-2	-1	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
46	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
47	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall	Preventive maintenance and replacement	Object - stretch	+3	+2	0	-1	+2	-2	0	+1	+1	0	0	0
48	Clear natural blockages such as shrubs and weeds	Preventive maintenance and replacement	Object	+1	0	-1	+2	-1	0	+1	0	0	+1	0	0
49	Construct detention storages	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
50	Cover slope with vegetation	Prevention	Regional network	+3	+2	+1	-2	0	+2	0	0	0	0	0	0
52	Develop plans and routines for the priority of securing areas prone to flooding	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
53	Drainage of road embankment for fast lowering of groundwater table after flood retreats	Upgrade / retrofitting / new construction	Object - stretch	+1	0	0	-1	+1	-2	-1	-1	-1	0	0	0
54	Dredge to increase depths and/or straighten the stream	Pro-active attitude	National network	+1	-1	0	-1	-1	-2	-1	+1	-2	0	0	0
55	Establish a guideline for standardized inspection of drainage system	Pro-active attitude	Regional network	+3	+2	+1	-2	0	+2	0	0	0	0	0	0
56	Improved models for bearing capacity of pavements after flooding	Research	Object - stretch - network	+2	0	+2	-1	+1	+2	0	0	0	+1	0	0
57	Inspect blue spots areas adjacent to heavy rainfalls	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
58	Inspect watercourses regularly	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
59	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
60	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
61	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
62	Keeping the road drainage in good condition	Preventive maintenance and replacement	Regional network	+2	+2	0	0	0	0	0	0	0	0	0	0
63	Lane closure	Extreme event management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
64	Make strategies for temporary rerouting	Pro-active attitude	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
65	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
66	Modal shift	Extreme event management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
67	Organize weirs/overflow towards storage facilities	Pro-active attitude	Object - stretch - network	+3	+3	+2	-2	0	+2	0	0	0	0	0	0
68	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
69	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
70	Prepare contingency / emergency plans	Pro-active attitude	National network	+3	+2	-1	-1	+2	0	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
71	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+1	+2	+1	+1	-1	+1	+2
72	Prevent the clogging of pipes/culverts on connecting roads	Preventive maintenance and replacement	Regional network	+2	+2	0	-1	0	0	0	0	0	0	0	0
73	Preventive information	Research	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
74	Real time traffic information	Traffic management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
75	Real time weather and traffic forecast	Traffic management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
76	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
77	Remove large obstructions (such as fallen trees or rubbish which restrict flow	Corrective maintenance and replacement	Object	+3	+2	0	+1	+1	+1	0	+1	-1	0	0	+1
78	Remove recent accumulations of debris which create obstructions to flow	Corrective maintenance and replacement	Object	+2	+1	0	-1	+1	+2	0	0	0	0	0	0
79	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0

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Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
80	Rerouting and guidance	Extreme event management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
81	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
82	Reviewing design storm return periods in the light of new weather information	Monitoring and prediction	Regional network	+1	0	0	-1	+2	+1	0	0	0	0	+1	+2
83	Revised standards for road design, avoiding buildup of water level differences	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0
84	Speed limits	Extreme event management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2
85	Use geosynthetics for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	0	+1	0	0
86	Use vegetation for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	+2	+1	0	0
87	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0
480	Apply porous asphalt surface course	Upgrade / retrofitting / new construction	Object - stretch - network	+1	0	+1	-3	+2	+2	0	0	0	-2	+2	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
481	Appropriate inspection and maintenance of in-pavement and road edge drainage	Preventive maintenance and replacement	Object - stretch - network	0	0	0	0	0	0	0	0	0	0	0	0
482	Increasing self-reliance of road users	Capacity building	Object - stretch - network	+1	+2	+2	+1	-1	+2	0	0	0	0	0	+2
483	Real time traffic information	Traffic management	Object - stretch - network	+1	+1	+1	-1	0	+2	+1	0	0	0	0	+2
484	Real time weather and traffic forecast	Traffic management	Object - stretch - network	-1	+2	-1	+2	-1	+2	-2	0	0	+1	0	+2
485	Speed limits	Traffic management	Object - stretch - network	-1	+2	0	0	0	+2	-2	0	0	+1	0	+2
486	Training of road owners for emergency situations	Capacity building	Object - stretch - network	0	+2	+1	0	+1	+2	0	0	0	0	0	+2
503	Appropriate inspection and maintenance of in-pavement and road edge drainage	Preventive maintenance and replacement	Object - stretch - network	0	0	0	0	0	0	0	0	0	0	0	0
504	Carriageway cross-over	Traffic management	Stretch	-2	-1	0	-2	-2	+1	+2	+2	0	-1	-1	+1
505	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+2	0	-1	-1	+1

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
506	Placing warning signs	Traffic management	Stretch	0	+2	0	+1	0	0	-2	0	0	0	0	+2
507	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+1	+2	+2	0	-1	-1	+1
508	Preventive information	Research	Object - stretch - network	-1	+2	-1	+2	-1	+2	-2	0	0	+1	0	+2
509	Real time traffic information	Traffic management	Object - stretch - network	-1	+2	-1	+2	-1	+2	-2	0	0	+1	0	+2
510	Real time weather and traffic forecast	Traffic management	Object - stretch - network	-1	+2	-1	+2	-1	+2	-2	0	0	+1	0	+2
511	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+2	0	-1	-1	+1
512	Reservoir pavements for hydrograph attenuation	Research	Stretch - network	+1	0	+1	-3	+2	+2	0	0	0	0	0	0
513	Reservoir pavements for water quality improvement	Research	Stretch - network	0	0	0	-3	0	+2	0	0	+2	0	0	0
514	Revised standards for in-pavement and road edge drainage	Prevention	Object - stretch - network	+1	+2	0	-1	0	+2	0	0	0	+1	0	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
515	Revised standards for materials in surface courses	Prevention	Object - stretch - network	+1	+2	0	0	0	+2	0	0	0	+1	0	+2
516	Speed limits	Traffic management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2
517	Systems for pavement surface drainage that are more reliable, and easier to inspect and maintain	Upgrade / retrofitting / new construction	Object - stretch - network	+1	0	+1	+1	0	+2	0	0	0	+1	0	0

Table 51: Assessment of measures for flooding of road surface due to failure of flood defence system and inundation in coastal areas (see chapter 2.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
1	Access restriction	Extreme event management	Stretch	+2	0	-2	+2	-1	+2	+2	+1	0	+1	0	0
2	Avoid deforestation in the catchment area	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
3	Build dams, reservoirs and retaining ponds to buffer the water	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0
4	Build flood walls to protect the road from flooding	Pro-active attitude	Object - stretch - network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
5	Carriageway cross-over	Extreme event management	Stretch	-2	-1	0	-2	-2	0	0	0	0	+1	+1	+2
6	Carrying out risk assessment of identified areas	Pro-active attitude	Object - stretch - network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
7	Clear natural blockages such as shrubs and weeds	Preventive maintenance and replacement	Object	+1	0	-1	+2	-1	0	+1	0	0	+1	0	0
8	Construction of (temporary) flood barriers along road	Extreme event management	Stretch	+2	+1	+1	-2	+1	0	0	0	0	0	0	+1

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Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
10	Develop plans and routines for the priority of securing areas prone to flooding	Pro-active attitude	Object - stretch - network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
11	Drainage of road embankment for fast lowering of groundwater table after flood retreats	Upgrade / retrofitting / new construction	Object - stretch	+1	0	0	-1	+1	-2	-1	-1	-1	0	0	0
12	Dredge to increase depths and/or straighten the stream	Pro-active attitude	National network	+1	-1	0	-1	-1	-2	-1	+1	-2	0	0	0
13	Elevated roads above High Water Level	Prevention	Stretch - network	+2	+2	+2	-3	+1	+2	0	0	0	-2	0	+2
15	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
16	Integration of infrastructure development and land use planning	Pro-active attitude	Regional network	+2	+2	+2	+2	+1	+2	0	0	+2	+2	0	+2
17	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0
18	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
19	Lane closure	Extreme event management	Stretch	-2	+3	0	-2	-2	0	+1	-1	+1	0	-1	+2
20	Make strategies for temporary rerouting	Pro-active attitude	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
21	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
22	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
23	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
24	Prepare contingency / emergency plans	Pro-active attitude	Regional network	0	+3	+1	0	-1	+2	0	0	0	0	0	+2
25	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+2	+2	+2	0	0	+1	+2
26	Preventive information	Research	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
27	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
28	Relocation of road	Prevention	Stretch - network	+2	+2	+2	-3	+2	+2	0	0	0	0	0	+2
29	Remove large obstructions (such as fallen trees or rubbish which restrict flow	Corrective maintenance and replacement	Object	+3	+2	0	+1	+1	+1	0	+1	-1	0	0	+1
30	Remove recent accumulations of debris which create obstructions to flow	Corrective maintenance and replacement	Object	+2	+1	0	-1	+1	+2	0	0	0	0	0	0
31	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
32	Rerouting and guidance	Extreme event management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+2	0	-1	-1	+1
33	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
34	Revised standards for road design, avoiding buildup of water level differences	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0
35	Shelter locations with facilities and life supplies, evacuation routes	Prevention	Regional network	0	+3	0	-2	+2	+2	0	0	0	0	0	+2
36	Speed limits	Extreme event management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2
37	Use geosynthetics for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	0	+1	0	0
38	Use vegetation for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	+2	+1	0	0
39	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0
96	Inspect and clean drainage systems regularly	Preventive maintenance and replacement	Object	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
103	Mangroves restoration to reduce wave run-up and shore erosion	Pro-active attitude	Regional network	+1	0	0	+1	+1	-1	+2	+2	+3	+2	+1	+2
105	Physical reinforcement of the coast line to protect against wave action	Pro-active attitude	Object - stretch	+2	0	0	-2	-1	+1	0	-3	-3	-2	-1	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria: Availability	Safety	Impact on network	Direct cost	Reputation	Contribution to sustainability criteria: General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
116	Reviewing design storm return periods in the light of new weather information	Monitoring and prediction	Regional network	0	0	0	0	0	0	0	0	0	0	0	0
118	Sand nourishment to reduce wave run-up and shore erosion	Pro-active attitude	Regional network	+1	0	0	+2	+1	-2	-1	+1	-1	-2	0	0

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Table 52: Assessment of measures for Flooding of road surface (assuming no traffic is possible) – Flooding due to failure of flood defence system of rivers and canals (see chapter 3.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
1	Access restriction	Extreme event management	Stretch	+2	0	-2	+2	-1	+2	+2	+1	0	+1	0	0
2	Avoid deforestation in the catchment area	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
3	Build dams, reservoirs and retaining ponds to buffer the water	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0
4	Build flood walls to protect the road from flooding	Pro-active attitude	Object - stretch - network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
5	Carriageway cross-over	Extreme event management	Stretch	-2	-1	0	-2	-2	0	0	0	0	+1	+1	+2
6	Carrying out risk assessment of identified areas	Pro-active attitude	Object - stretch - network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
7	Clear natural blockages such as shrubs and weeds	Preventive maintenance and replacement	Object	+1	0	-1	+2	-1	0	+1	0	0	+1	0	0
8	Construction of (temporary) flood barriers along road	Extreme event management	Stretch	+2	+1	+1	-2	+1	0	0	0	0	0	0	+1

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
9	Develop plans and routines for the priority of securing areas prone to flooding	Pro-active attitude	Object - stretch - network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
10	Drainage of road embankment for fast lowering of groundwater table after flood retreats	Upgrade / retrofitting / new construction	Object - stretch	+1	0	0	-1	+1	-2	-1	-1	-1	0	0	0
11	Dredge to increase depths and/or straighten the stream	Pro-active attitude	National network	+1	-1	0	-1	-1	-2	-1	+1	-2	0	0	0
12	Elevated roads above High Water Level	Prevention	Stretch - network	+2	+2	+2	-3	+1	+2	0	0	0	-2	0	+2
13	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
14	Integration of infrastructure development and land use planning	Pro-active attitude	Regional network	+2	+2	+2	+2	+1	+2	0	0	+2	+2	0	+2
15	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0
16	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
17	Lane closure	Extreme event management	Stretch	-2	+3	0	-2	-2	0	+1	-1	+1	0	-1	+2
18	Make strategies for temporary rerouting	Pro-active attitude	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
19	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
20	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
21	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
22	Prepare contingency / emergency plans	Pro-active attitude	Regional network	0	+3	+1	0	-1	+2	0	0	0	0	0	+2
23	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+2	+2	+2	0	0	+1	+2
24	Preventive information	Research	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
25	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
26	Relocation of road	Prevention	Stretch - network	+2	+2	+2	-3	+2	+2	0	0	0	0	0	+2
27	Remove large obstructions (such as fallen trees or rubbish which restrict flow	Corrective maintenance and replacement	Object	+3	+2	0	+1	+1	+1	0	+1	-1	0	0	+1
28	Remove recent accumulations of debris which create obstructions to flow	Corrective maintenance and replacement	Object	+2	+1	0	-1	+1	+2	0	0	0	0	0	0
29	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
30	Rerouting and guidance	Extreme event management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+2	0	-1	-1	+1
31	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
32	Revised standards for road design, avoiding buildup of water level differences	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0
33	Shelter locations with facilities and life supplies, evacuation routes	Prevention	Regional network	0	+3	0	-2	+2	+2	0	0	0	0	0	+2
34	Speed limits	Extreme event management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2
35	Use geosynthetics for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	0	+1	0	0
36	Use vegetation for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	+2	+1	0	0
37	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0

Table 53: Assessment of measures for Flooding of road surface (assuming no traffic is possible) – Pluvial flooding (see chapter 3.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
38	Access restriction	Extreme event management	Stretch	+2	0	-2	+2	-1	+2	+2	+1	0	+1	0	0
39	Avoid deforestation in the catchment area	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
40	Build flood walls to protect the road from flooding	Pro-active attitude	National network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
41	Build flood walls to protect the road from flooding	Pro-active attitude	National network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
42	Carriageway cross-over	Extreme event management	Stretch	-2	-1	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
43	Carriageway cross-over	Extreme event management	Stretch	-2	-1	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
44	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
45	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall	Preventive maintenance and replacement	Object - stretch	+3	+2	0	-1	+2	-2	0	+1	+1	0	0	0
46	Clear natural blockages such as shrubs and weeds	Preventive maintenance and replacement	Object	+1	0	-1	+2	-1	0	+1	0	0	+1	0	0

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Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
47	Construct detention storages	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0
48	Cover slope with vegetation	Prevention	Regional network	+3	+2	+1	-2	0	+2	0	0	0	0	0	0
49	Develop plans and routines for the priority of securing areas prone to flooding	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
50	Drainage of road embankment for fast lowering of groundwater table after flood retreats	Upgrade / retrofitting / new construction	Object - stretch	+1	0	0	-1	+1	-2	-1	-1	-1	0	0	0
51	Dredge to increase depths and/or straighten the stream	Pro-active attitude	National network	+1	-1	0	-1	-1	-2	-1	+1	-2	0	0	0
52	Establish a guideline for standardized inspection of drainage system	Pro-active attitude	Regional network	+3	+2	+1	-2	0	+2	0	0	0	0	0	0
53	Inspect blue spots areas adjacent to heavy rainfalls	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
54	Inspect watercourses regularly	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
55	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
56	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
57	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
58	Keeping the road drainage in good condition	Preventive maintenance and replacement	Regional network	+2	+2	0	0	0	0	0	0	0	0	0	0
59	Lane closure	Extreme event management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
60	Make strategies for temporary rerouting	Pro-active attitude	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
61	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
62	Modal shift	Extreme event management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
63	Organize weirs/overflow towards storage facilities	Pro-active attitude	Object - stretch - network	+3	+3	+2	-2	0	+2	0	0	0	0	0	0
64	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
65	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
66	Prepare contingency / emergency plans	Pro-active attitude	National network	+3	+2	-1	-1	+2	0	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
67	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+1	+2	+1	+1	-1	+1	+2
68	Prevent the clogging of pipes/culverts on connecting roads	Preventive maintenance and replacement	Regional network	+2	+2	0	-1	0	0	0	0	0	0	0	0
69	Preventive information	Research	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
70	Real time traffic information	Traffic management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
71	Real time weather and traffic forecast	Traffic management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
72	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
73	Remove large obstructions (such as fallen trees or rubbish which restrict flow	Corrective maintenance and replacement	Object	+3	+2	0	+1	+1	+1	0	+1	-1	0	0	+1
74	Remove recent accumulations of debris which create obstructions to flow	Corrective maintenance and replacement	Object	+2	+1	0	-1	+1	+2	0	0	0	0	0	0
75	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
76	Rerouting and guidance	Extreme event management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
77	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
78	Reviewing design storm return periods in the light of new weather information	Monitoring and prediction	Regional network	+1	0	0	-1	+2	+1	0	0	0	0	+1	+2
79	Revised standards for road design, avoiding buildup of water level differences	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0
80	Speed limits	Extreme event management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2
81	Use geosynthetics for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	0	+1	0	0
82	Use vegetation for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	+2	+1	0	0
83	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0

Table 54: Assessment of measures for Flooding of road surface (assuming no traffic is possible) – Inundation of roads in coastal areas, combining the effects of sea level rise and storm surges (see chapter 3.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
84	Access restriction	Extreme event management	Stretch	+2	0	-2	+2	-1	+2	+2	+1	0	+1	0	0
85	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
86	Construction of (temporary) flood barriers along road	Extreme event management	Stretch	+2	+1	+1	-2	+1	0	0	0	0	0	0	+1
87	Develop plans and routines for the priority of securing areas prone to flooding	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
88	Drainage of road embankment for fast lowering of groundwater table after flood retreats	Upgrade / retrofitting / new construction	Object - stretch	+1	0	0	-1	+1	-2	-1	-1	-1	0	0	0
89	Elevated roads above High Water Level	Prevention	Stretch - network	+2	+2	+2	-3	+1	+2	0	0	0	-2	0	+2
90	Inspect and clean drainage systems regularly	Preventive maintenance and replacement	Object	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
91	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
92	Integration of infrastructure development and land use planning	Pro-active attitude	Regional network	+2	+2	+2	+2	+1	+2	0	0	+2	+2	0	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
93	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0
94	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
95	Lane closure	Extreme event management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
96	Make strategies for temporary rerouting	Pro-active attitude	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
97	Mangroves restoration to reduce wave run-up and shore erosion	Pro-active attitude	Regional network	+1	0	0	+1	+1	-1	+2	+2	+3	+2	+1	+2
98	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
99	Physical reinforcement of the coast line to protect against wave action	Pro-active attitude	Object - stretch	+2	0	0	-2	-1	+1	0	-3	-3	-2	-1	0
100	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
101	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
102	Prepare contingency / emergency plans	Pro-active attitude	Regional network	0	+3	+1	0	-1	+2	0	0	0	0	0	+2
103	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+1	+2	+1	+1	-1	+1	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
104	Preventive information	Research	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
105	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
106	Relocation of road	Prevention	Stretch - network	+2	+2	+2	-3	+2	+2	0	0	0	0	0	+2
107	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
108	Rerouting and guidance	Extreme event management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+1	+1	-1	+1	+2
109	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
110	Reviewing design storm return periods in the light of new weather information	Monitoring and prediction	Regional network	0	0	0	0	0	0	0	0	0	0	0	0
111	Revised standards for road design, avoiding buildup of water level differences	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0
112	Sand nourishment to reduce wave run-up and shore erosion	Pro-active attitude	Regional network	+1	0	0	+2	+1	-2	-1	+1	-1	-2	0	0
113	Shelter locations with facilities and life supplies, evacuation routes	Prevention	Regional network	0	+3	0	-2	+2	+2	0	0	0	0	0	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
114	Speed limits	Extreme event management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2
115	Use geosynthetics for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	0	+1	0	0
116	Use vegetation for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	+2	+1	0	0
117	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0

Table 55: Assessment of measures for Flooding of road surface (assuming no traffic is possible) – Flooding from snow melt (overland flow after snow melt, see chapter 3.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
118	Access restriction	Extreme event management	Stretch	+2	0	-2	+2	-1	+2	+2	+1	0	+1	0	0
119	Build flood walls to protect the road from flooding	Pro-active attitude	National network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
120	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
121	Cleaning out watercourses and structures of flood prone areas ahead of predicted snow melt	Preventive maintenance and replacement	Object - stretch	+3	+2	0	-1	+2	-2	0	+1	+1	0	0	0
122	Clear natural blockages such as shrubs and weeds	Preventive maintenance and replacement	Object	+1	0	-1	+2	-1	0	+1	0	0	+1	0	0
123	Construct detention storages	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0
124	Develop plans and routines for the priority of securing areas prone to flooding	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
125	Drainage of road embankment for fast lowering of groundwater table after flood retreats	Upgrade / retrofitting / new construction	Object - stretch	+1	0	0	-1	+1	-2	-1	-1	-1	0	0	0
126	Dredge to increase depths and/or straighten the stream	Pro-active attitude	National network	+1	-1	0	-1	-1	-2	-1	+1	-2	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
127	Inspect blue spots areas adjacent to snow melt	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
128	Inspect watercourses regularly	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
129	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
130	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0
131	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
132	Make strategies for temporary rerouting	Pro-active attitude	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
133	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
134	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
135	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
136	Prepare contingency / emergency plans	Pro-active attitude	National network	+3	+2	-1	-1	+2	0	0	0	0	0	0	0
137	Preventive information	Research	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
138	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
139	Remove large obstructions (such as fallen trees or rubbish which restrict flow	Corrective maintenance and replacement	Object	+3	+2	0	+1	+1	+1	0	+1	-1	0	0	+1
140	Remove recent accumulations of debris and ice which create obstructions to flow	Corrective maintenance and replacement	Object	+2	+1	0	-1	+1	+2	0	0	0	0	0	0
141	Remove snow and ice from the road	Corrective maintenance and replacement	National network	+2	+1	+1	-1	+2	-2	-1	+2	-1	0	0	0
142	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
143	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
144	Reviewing design storm return periods in the light of new weather information	Monitoring and prediction	Regional network	+1	0	0	-1	+2	+1	0	0	0	0	+1	+2
145	Use geosynthetics for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	0	+1	0	0
146	Use vegetation for improving slope stability and erosion protection	Upgrade / retrofitting / new construction	Object - stretch	+2	0	+1	-2	0	+2	0	0	+2	+1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
147	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0

Table 56: Assessment of measures for Impact of flooding on soil moisture levels, affecting the structural integrity of roads, bridges and tunnels (see chapter 3.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
342	Access restriction	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
343	Application of geotextiles in (sub)base	Upgrade / retrofitting / new construction	Stretch	+1	0	0	-1	0	+2	0	0	0	+1	0	0
344	Develop binders that are more resilient to stripping	Research	Object - stretch - network	+1	+1	0	-1	0	+2	0	0	0	+1	0	+1
345	Full depth patches	Corrective maintenance and replacement	Object	0	0	0	0	0	0	0	0	0	-1	0	0
346	Improving drainage of the area	Prevention	Regional network	+2	0	+2	-1	-1	+2	0	0	0	0	0	0
347	Improved models for bearing capacity of pavements after flooding	Research	Object - stretch - network	+2	0	+2	-1	+1	+2	0	0	0	+1	0	0
348	In situ strengthening of granular (sub)bases and subgrade soils, using articificial or natural cements	Research	Stretch	+1	0	+1	-2	0	+2	0	0	0	0	0	0
349	Increase the thickness of structural layers	Upgrade / retrofitting / new construction	Object - stretch	+1	0	+1	-1	0	+2	0	0	0	0	0	0
350	Keeping the road drainage in good condition	Preventive maintenance and replacement	Regional network	0	0	0	0	0	0	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
351	Lowering the groundwater table within the road embankment with deeper drainage	Prevention	Object - stretch	+1	0	+1	-1	0	+2	0	0	0	0	0	0
352	Modal shift	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
353	Monitoring to detect potential problem areas, establish cause-impact relationships; maintain specific construction and maintenance records	Monitoring and prediction	Stretch	0	0	0	0	0	0	0	0	0	+1	0	0
552	Monitoring of water levels in the road embankment after flooding	Monitoring and prediction	Stretch	+1	0	+1	0	+1	+1	0	0	0	+1	0	0
354	Preventive information	Research	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
355	Real time traffic information	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
356	Real time weather and traffic forecast	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
357	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+1	+1	-1	+1	+2
358	Revised standards for binder course, (sub)base and subgrade materials, drainage	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0

Table 57: Assessment of measures for Landslides (see chapter 3.2.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
245	Assess the risk of landslides based on pore pressure	Research	National network	-3	-1	0	-2	-1	0	0	+1	0	0	0	0
246	Avoid deforestation on slopes	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
247	Carriageway cross-over	Traffic management	Stretch	-2	-1	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
248	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
249	Continuously measure the pore pressure in the slope	Monitoring and prediction	Object - stretch	+3	+1	0	-2	+1	-2	0	0	0	0	0	0
250	Cover slope with rock blanket	Prevention	Object	+2	+3	-1	+2	+2	+2	-1	-1	-3	-3	0	0
251	Cover slope with vegetation	Prevention	Object	+3	+1	0	-1	+1	-1	+1	0	+2	+1	0	0
252	Cutting back the slope to a shallower angle	Prevention	Object	+1	+2	-1	-1	+2	-1	0	-1	-1	0	0	0
253	Develop plans and routines for the priority of securing areas prone to landslides	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
254	Implement a system of geotechnical risk management	Pro-active attitude	National network	+2	+1	0	+1	+1	-1	0	0	0	0	0	0
256	Inspect and clean watercourses regularly	Preventive maintenance and replacement	Object - stretch - network	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
257	Install erosion barriers soon after the wildfire	Pro-active attitude	Object	+3	+2	0	-1	+1	+1	0	0	+1	-1	+1	+1
258	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
259	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
260	Mapping areas prone to landslides	Pro-active attitude	Regional network	+2	+1	0	-1	+1	0	0	0	0	0	0	0
261	Mapping sites of occurred landslides	Pro-active attitude	Regional network	0	0	0	0	0	0	0	0	0	0	0	0
262	Rebuild stretches of the road on safe ground	Upgrade / retrofitting / new construction	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
263	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
264	Spread mulch over the soil to protect it	Prevention	Object	+3	+1	0	-1	+1	0	0	+1	+2	0	+1	0
265	Stabilize the surrounding area	Extreme event management	Object	+2	+2	+1	-2	+2	-1	0	0	0	0	0	0
266	Study the relationship between intense rainfalls and landslides to create threshold levels of when to expect landslides	Research	National network	+1	+1	0	-1	+2	-2	0	0	0	0	0	0
267	Support the slope with a retaining structure	Prevention	Object	+3	0	0	-2	+2	-2	0	-1	-2	-2	0	0

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Table 58: Assessment of measures for Slides of the road embankment (see chapter 3.2.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
268	Assess the risk of landslides based on pore pressure	Research	National network	-3	-1	0	-2	-1	0	0	+1	0	0	0	0
269	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
270	Continuously measure the pore pressure in the slope	Monitoring and prediction	Object - stretch	+3	+1	0	-2	+1	-2	0	0	0	0	0	0
271	Cover slope with rock blanket	Prevention	Object	+2	+3	-1	+2	+2	+2	-1	-1	-3	-3	0	0
272	Cover slope with vegetation	Prevention	Object	+3	+1	0	-1	+1	-1	+1	0	+2	+1	0	0
273	Cutting back the slope to a shallower angle	Prevention	Object	+1	+2	-1	-1	+2	-1	0	-1	-1	0	0	0
274	Develop plans and routines for the priority of securing areas prone to landslides	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
275	Ensure efficient drainage systems	Pro-active attitude	Object - stretch	+1	0	0	-1	+1	0	0	0	0	0	0	0
276	Implement a system of geotechnical risk management	Pro-active attitude	National network	+2	+1	0	+1	+1	-1	0	0	0	0	0	0
277	Inspect and clean watercourses regularly	Preventive maintenance and replacement	Object - stretch - network	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
278	Install erosion barriers soon after the wildfire	Pro-active attitude	Object	+3	+2	0	-1	+1	+1	0	0	+1	-1	+1	+1
279	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
280	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0

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Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
281	Mapping areas prone to landslides	Pro-active attitude	Regional network	+2	+1	0	-1	+1	0	0	0	0	0	0	0
282	Mapping sites of occurred landslides	Pro-active attitude	Regional network	0	0	0	0	0	0	0	0	0	0	0	0
283	Rebuild stretches of the road on safe ground	Upgrade / retrofitting / new construction	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
284	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
285	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
286	Stabilize the surrounding area	Extreme event management	Object	+2	+2	+1	-2	+2	-1	0	0	0	0	0	0
287	Study the relationship between intense rainfalls and landslides to create threshold levels of when to expect landslides	Research	National network	+1	+1	0	-1	+2	-2	0	0	0	0	0	0
288	Support the slope with a retaining structure	Prevention	Object	+3	0	0	-2	+2	-2	0	-1	-2	-2	0	0

Table 59: Assessment of measures for Debris flow (see chapter 3.2.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
289	Avoid deforestation on slopes	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
290	Build channels or deflection walls to direct the flow	Pro-active attitude	Object	+2	+2	0	-2	+2	+2	0	-1	-1	-2	0	0
291	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
292	Construct a catch ditch at the toe of the slope	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	-1	0	+1	0	0	0	0
293	Develop plans and routines for the priority of securing areas prone to debris flows	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
294	Ensure efficient drainage systems	Pro-active attitude	Object - stretch	+1	0	0	-1	+1	0	0	0	0	0	0	0
295	Implement a system of geotechnical risk management	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
296	Inspect and clean watercourses regularly	Preventive maintenance and replacement	Object - stretch - network	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
297	Install barriers to catch material in debris flows	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
298	Install dams to arrest and store debris	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
299	Install protective walls/barriers to divert masses	Pro-active attitude	Object	+2	+1	0	-1	+1	0	-1	-2	-2	-1	0	0
300	Install sheds or walls to protect roads	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-2	-2	-1	0	0
301	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
302	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
303	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
304	Mapping areas prone to debris flows	Pro-active attitude	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
305	Mapping sites of occurred debris flows	Pro-active attitude	Regional network	+2	+1	0	-1	+1	0	0	0	0	0	0	0
306	Rebuild stretches of the road on safe ground	Upgrade / retrofitting / new construction	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
307	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
308	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
309	Study the relationship between intense rainfalls and debris flows to create threshold levels of when to expect a failure	Research	National network	+1	+1	0	-1	+2	-2	0	0	0	0	0	0
310	Use sensitive seismographs to detect debris flows that have already started moving	Pro-active attitude	Object - stretch - network	-1	0	0	-2	+1	-1	0	0	0	0	0	0

Table 60: Assessment of measures for Rock fall (see chapter 3.2.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
311	Apply Rockfall Hazard Rating System (RHRS) on the slope	Pro-active attitude	Object - stretch	0	+1	0	-1	0	0	0	0	0	0	0	0
312	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
313	Construct a catch ditch at the toe of the slope	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	-1	0	+1	0	0	0	0
314	Develop plans and routines for the priority of securing areas prone to rock falls	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
315	Ensure efficient drainage systems	Pro-active attitude	Object - stretch	+1	0	0	-1	+1	0	0	0	0	0	0	0
316	Implement a system of geotechnical risk management	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
317	Install active protection systems to prevent rock detachments.	Prevention	Object - stretch - network	-1	+2	0	-2	+2	-2	0	0	0	0	0	0
318	Install passive protection systems to protect infrastructure below the slope	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-2	-2	-1	0	0
319	Install sheds or walls to protect roads	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-2	-2	-1	0	0
320	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
321	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
322	Mapping areas prone to rock falls	Pro-active attitude	Regional network	+2	+1	0	-1	+1	0	0	0	0	0	0	0
323	Mapping sites of occurred rock falls	Pro-active attitude	Regional network	+3	+1	0	-1	+2	-1	0	0	0	0	0	0
324	Perform controlled explosions or other measures to remove loose rocks	Preventive maintenance and replacement	Object - stretch - network	+2	-1	-1	-2	+1	-1	-1	-1	-2	-2	0	0
325	Perform regular laser monitoring to detect movement of rocks	Monitoring and prediction	Object - stretch - network	+2	-1	-1	-2	+1	-1	-1	-1	-2	-2	0	0
326	Rebuild stretches of the road on safe ground	Upgrade / retrofitting / new construction	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
327	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
328	Study the relationship between rock fall and precipitation	Research	Regional network	+1	0	0	-1	+1	-1	0	0	0	0	0	0

Table 61: Assessment of measures for Snow avalanches (see chapter 3.2.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
329	Artificial triggering (active control) of avalanches	Pro-active attitude	Object - stretch - network	+3	-1	-1	-2	+2	-2	-2	+1	-1	-1	-1	0
330	Avoid deforestation on slopes	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
331	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
332	Develop plans and routines for the priority of securing areas prone to avalanches	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
333	Install dams to arrest and store snow	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-1	+1	-1	0	0
334	Install sheds or walls to protect roads	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-2	-2	-1	0	0
335	Install supporting structures in the starting zone	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-2	-2	-1	0	0
336	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
337	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
338	Mapping areas prone to avalanches	Pro-active attitude	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0

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Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
339	Mapping sites of occurred avalanches	Pro-active attitude	Regional network	+3	+1	0	-1	+2	-1	0	0	0	0	0	0
340	Rebuild stretches of the road on safe ground	Upgrade / retrofitting / new construction	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
341	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
329	Artificial triggering (active control) of avalanches	Pro-active attitude	Object - stretch - network	+3	-1	-1	-2	+2	-2	-2	+1	-1	-1	-1	0
330	Avoid deforestation on slopes	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
331	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
332	Develop plans and routines for the priority of securing areas prone to avalanches	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
333	Install dams to arrest and store snow	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-1	+1	-1	0	0
334	Install sheds or walls to protect roads	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-2	-2	-1	0	0
335	Install supporting structures in the starting zone	Pro-active attitude	Object - stretch - network	+2	+1	0	-1	+1	0	-1	-2	-2	-1	0	0
336	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
337	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
338	Mapping areas prone to avalanches	Pro-active attitude	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
339	Mapping sites of occurred avalanches	Pro-active attitude	Regional network	+3	+1	0	-1	+2	-1	0	0	0	0	0	0
340	Rebuild stretches of the road on safe ground	Upgrade / retrofitting / new construction	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
341	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0

Table 62: Assessment of measures for Loss of road structure integrity – Uplift of tunnels or light weight construction materials by increasing water levels (see chapter 3.3.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
401	Adapt drainage system to control ground water table	Upgrade / retrofitting / new construction	Object - stretch	+2	+1	+2	-2	0	+2	0	0	0	+1	0	0
402	Apply structural surcharge to counter uplift	Upgrade / retrofitting / new construction	Object - stretch	+2	+1	+2	-2	0	+2	-2	0	-2	-2	0	0
403	Apply surcharge to counter uplift as emergency measure	Extreme event management	Object - stretch	+1	0	0	-1	0	+2	-1	0	-1	-1	0	+2
404	Appropriate inspection and maintenance of drainage, pumping and waterproofing systems	Preventive maintenance and replacement	Object - stretch	+1	0	0	+1	0	0	0	0	0	0	0	0
405	Collect relevant construction data	Pro-active attitude	Object - stretch	0	0	0	0	0	0	0	0	0	+1	0	0
406	Install pumping systems to control ground water table	Upgrade / retrofitting / new construction	Object - stretch	+2	+1	+2	-2	0	+2	-2	0	-2	-1	0	0
407	Modal shift	Traffic management	Regional network	+1	0	0	-1	0	+2	0	0	0	+1	0	+2
408	Monitor ground water table	Monitoring and prediction	Object - stretch	0	0	0	-1	0	0	0	0	0	+1	0	0
409	Prepare contingency / emergency plans	Pro-active attitude	Object - stretch	0	+2	0	0	0	+2	-2	0	0	+1	0	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
410	Preventive information	Research	Object - stretch - network	+1	0	0	-1	0	+2	0	0	0	+1	0	+2
411	Real time traffic information	Traffic management	Regional network	+1	0	0	-1	0	+2	0	0	0	+1	0	+2
412	Rerouting and guidance	Traffic management	Regional network	+1	0	0	-1	0	+2	0	0	0	+1	0	+2
413	Revised standards for design of excavations and light weight fills	Prevention	Object - stretch	+2	+1	+2	0	0	+2	0	0	0	+1	0	0
414	Strengthen tension piles of excavations	Upgrade / retrofitting / new construction	Object - stretch	+2	+1	+2	-2	0	+2	0	0	0	+1	0	0

Table 63: Assessment of measures for Erosion due to overloading of hydraulic systems (see chapter 3.4.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
148	Avoid deforestation in the catchment area	Pro-active attitude	Object - stretch - network	+3	+1	0	-1	+2	0	+3	+3	+3	0	+2	+2
149	Avoid urbanisation and watersheds diversions in vulnerable areas	Pro-active attitude	Object - stretch	+3	+1	0	-1	0	0	+2	-1	+3	+1	0	0
150	Build dams, reservoirs and retaining ponds to buffer the water	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0
151	Build flood walls to protect the road from flooding	Pro-active attitude	National network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
152	Carriageway cross-over	Traffic management	Stretch	-2	-1	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
153	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
154	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall	Preventive maintenance and replacement	Object - stretch	+3	+2	0	-1	+2	-2	0	+1	+1	0	0	0
155	Clear natural blockages such as shrubs and weeds	Preventive maintenance and replacement	Object	+1	0	-1	+2	-1	0	+1	0	0	+1	0	0
156	Cover road embankment with geotextile	Prevention	Object - stretch	+3	+1	0	+2	+1	+2	0	-1	-1	-1	-1	0
157	Cover slope with rock blanket	Prevention	Object - stretch	+2	+3	-1	+2	+2	+2	-1	-1	-3	-3	0	0
158	Cover slope with vegetation	Prevention	Regional network	+3	+2	+1	-2	0	+2	0	0	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
159	Develop plans and routines for the priority of securing areas prone to overloaded hydraulic systems	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
160	Dredge to increase depths and/or straighten the stream	Pro-active attitude	National network	+1	-1	0	-1	-1	-2	-1	+1	-2	0	0	0
161	Establish a guideline for standardized inspection of culverts	Preventive maintenance and replacement	Object - stretch - network	+3	+1	+1	-2	0	+2	0	0	0	0	0	0
162	Inspect and clean watercourses regularly	Preventive maintenance and replacement	Object	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
163	Inspect blue spots areas adjacent to heavy rainfalls	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
164	Install sign posts warning for flooding in threatened areas	Traffic management	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
165	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+1	0	0	+1	-1	0	0	0	0	0	0
166	Keeping records of events and locations of overloaded hydraulic systems	Pro-active attitude	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
167	Keeping records of flooding events and locations	Monitoring and prediction	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
168	Lane closure	Traffic management	Stretch	-2	+3	0	-2	-2	+1	+2	+1	+1	-1	+1	+2
169	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
170	Mapping areas prone to flooding (Blue spot analysis)	Monitoring and prediction	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
171	Modal shift	Extreme event management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
172	Organize weirs/overflow towards storage facilities	Pro-active attitude	Object - stretch - network	+3	+3	+2	-2	0	+2	0	0	0	0	0	0
173	Pave the inlet and the outlet of the culvert	Pro-active attitude	Object - stretch	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
174	Prepare and educate road users for flooding	Capacity building	Object - stretch - network	0	+2	+2	-1	+2	+2	+2	+2	0	+1	0	+2
175	Prepare and educate staff for flooding	Capacity building	Object - stretch - network	0	+1	+2	-1	0	+2	0	0	0	+1	0	+1
176	Prepare Traffic Management Plans	Traffic management	TEN-T - national - regional	+2	+1	+3	-1	+2	+1	+2	+1	+1	-1	+1	+2
177	Protect entrance embankment with rock blanket	Prevention	Object	+2	+1	0	-1	0	-1	-1	-1	-1	-1	0	0
178	Protect entrance against floating debris	Prevention	Object	+2	+1	0	-1	0	-1	-1	-1	-1	-1	0	0
179	Real time traffic information	Traffic management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
180	Real time weather and traffic forecast	Traffic management	TEN-T - national - regional	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
181	Rebuild stretches of the road on safe ground	Prevention	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
182	Replace the culvert with a small bridge	Upgrade / retrofitting / new construction	Object	+2	+1	0	-2	0	-1	-1	-1	-1	-1	0	0
183	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
184	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+1	+1	-1	+1	+2
185	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
186	Reviewing design storm return periods in the light of new weather information	Monitoring and prediction	Regional network	+1	0	0	-1	+2	+1	0	0	0	0	+1	+2
187	Revised standards for design of culverts	Prevention	National network	+1	+2	0	-2	0	+2	0	0	0	+1	0	+1
188	Revised standards for road design, avoiding buildup of water level differences	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0
189	Speed limits	Traffic management	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
190	Take measures to reduce downstream sedimentation and clean debris and sediment from the outlet ditch afterwards.	Prevention	Object	+2	+1	0	-2	+1	+2	-1	-1	-3	-3	0	0
191	Wetland restoration as part of a strategy of multiply lines of flood defences	Pro-active attitude	Regional network	+1	+1	0	-2	+2	0	+1	+2	+3	0	+2	0

Table 64: Assessment of measures for Erosion of road bases (see chapter 3.4.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
192	Build flood walls to protect the road from flooding	Pro-active attitude	National network	+2	+1	0	-2	-1	-1	-1	+2	-2	-1	-1	0
193	Carrying out risk assessment of identified areas	Pro-active attitude	Regional network	+1	+2	+1	-2	+2	-2	-1	+1	0	0	0	0
194	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall	Prevention	Object - stretch	+3	+2	0	-1	+2	-2	0	+1	+1	0	0	0
195	Construct detention storages	Pro-active attitude	Object - stretch - network	+2	0	0	-1	+2	+1	0	0	+2	-1	0	0
196	Cover road embankment with geotextile	Prevention	Object - stretch	+3	+1	0	+2	+1	+2	0	-1	-1	-1	-1	0
197	Cover slope with rock blanket	Prevention	Object - stretch	+2	+3	-1	+2	+2	+2	-1	-1	-3	-3	0	0
198	Cover slope with vegetation	Prevention	Object - stretch	+3	+1	0	-1	+1	-1	+1	0	+2	+1	0	0
199	Cover the road embankment with hard protection to reduce wave action	Prevention	Object - stretch	+2	+3	-1	+2	+2	+2	-1	-1	-3	-3	0	0
200	Develop plans and routines for the priority of securing areas prone to be affected by sea level rise	Pro-active attitude	Regional network	+1	+2	-1	-1	+2	0	0	0	0	0	0	0
201	Flatten the road embankment	Pro-active attitude	Object - stretch	+1	+1	0	-1	+1	+3	0	-1	0	0	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
202	Inspect watercourses regularly	Preventive maintenance and replacement	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
203	Install or raise the level of existing protecting wall outside the road	Prevention	Object - stretch	+1	+1	0	-2	0	+1	0	0	-1	-1	0	0
204	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0
205	Keeping records of flooding events and locations	Pro-active attitude	Regional network	+2	+1	0	-1	+1	-2	0	0	0	0	0	0
206	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
207	Mapping areas prone to flooding (Blue spot analysis)	Pro-active attitude	Regional network	+2	+1	0	-1	+2	-1	0	0	0	0	0	0
208	Rebuild stretches of the road on safe ground	Upgrade / retrofitting / new construction	Stretch	+1	+1	-1	-2	-1	-2	-2	-2	-1	-2	0	0
209	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
210	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
211	Reviewing design storm return periods in the light of new weather information	Research	Regional network	+1	0	0	-1	+2	+1	0	0	0	0	+1	+2
212	Vegetation along the slope of the road embankment to reduce wave action and stream velocity	Pro-active attitude	Regional network	+1	+1	0	-1	+1	-1	+1	0	+1	0	0	0

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Table 65: Assessment of measures for Bridge scour (see chapter 3.4.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
213	Check dams - installing sills or drop structures	Pro-active attitude	Object - stretch	+2	0	0	-2	+1	0	-1	+1	+1	+2	0	0
214	Cleaning out watercourses and structures of flood prone areas ahead of predicted heavy rainfall	Prevention	Object - stretch	+3	+2	0	-1	+2	-2	0	+1	+1	0	0	0
215	Dredge the channel to increase the width and/or depth	Prevention	Object - stretch	+3	+1	-2	-2	-1	-1	0	-1	-2	0	-1	0
216	Extend the footing to support the slope or protect it from erosion	Pro-active attitude	Object	+2	+1	0	-1	+1	+2	0	0	-1	-1	0	0
217	Increase span/relief bridge	Upgrade / retrofitting / new construction	Object	+1	+1	+1	-3	+1	+3	-1	+1	0	-1	0	0
218	Inspect bridge foundations and surroundings (over and under water) regularly	Preventive maintenance and replacement	Object	+3	+2	0	+2	+2	-1	0	+1	0	0	0	0
219	Install a bulkhead to support the slope and protect it from erosion	Prevention	Object	+2	+2	-1	-2	+2	+2	-1	-1	-3	-3	0	0
220	Install debris basins to collect debris	Pro-active attitude	Object	+2	+1	0	-1	0	+2	-1	-1	-3	-3	0	0
221	Install flexible revetment as artifical armoring	Prevention	Object	0	+1	0	+1	0	+1	0	-1	-1	0	-1	0
222	Install flow deflecting plates to deflect flow	Prevention	Object	-1	0	0	+1	0	-1	0	-1	-1	-1	-1	0
223	Install jetties to support the slope or protect bank from erosion	Prevention	Object - stretch	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
224	Install vanes upstreams to reduce flow	Pro-active attitude	Object	-1	0	0	+1	0	-1	0	0	-1	-1	0	0
225	Keeping in-house GIS up to date	Pro-active attitude	Regional network	+3	+2	0	-1	+2	-1	0	0	0	0	0	0
226	Make strategies for temporary rerouting	Traffic management	Regional network	+3	+1	+2	-1	+2	-2	-1	-1	0	0	-1	0
227	Plant vegetation to prevent bank erosion	Prevention	Object - stretch	+2	+1	0	-1	+1	+1	+1	+2	+3	0	+2	+1
228	Protect foundation and surroundings with gabions/ reno mattress	Prevention	Object	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
229	Protect foundations and surroundings with bituminous concrete pavement	Prevention	Object	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
230	Protect foundations and surroundings with fabric bags filled with concrete and stacked to produce a protective layer	Prevention	Object	+2	+2	-1	-2	-2	-1	-1	-1	-3	-3	-1	0
231	Protect foundations and surroundings with guide banks (spurs/dyke)	Prevention	Object	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
232	Protect foundations and surroundings with rock or gravel blankets	Prevention	Object	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
233	Protect foundations or surroundings with artificial riprap or tetrapods /toskanes	Prevention	Object	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
234	Protect foundations or surroundings with cable-tied blocks	Prevention	Object	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
235	Protect foundations or surroundings with concrete grouted riprap	Prevention	Object	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
236	Protect foundations or surroundings with precast concrete blocks with retard (timber & sheet piles)	Prevention	Object	+2	+3	-1	-2	+2	+2	-1	-1	-3	-3	0	0
237	Protect foundations or surroundings with sacrificial piles upstream to reduce velocity	Prevention	Object	0	+1	0	-1	0	+1	0	-1	-3	-3	0	0
238	Protect foundations with structures that dissipate energy in the water	Prevention	Object	0	+1	0	-1	0	+1	0	-1	-3	-3	0	0
239	Reroute the traffic	Extreme event management	Stretch - network	+2	0	-3	-2	+1	0	-2	-3	0	-1	0	0
240	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+1	+1	-1	+1	+2
241	Resize drainage systems to meet threats	Upgrade / retrofitting / new construction	Object - stretch - network	+3	+1	-1	-2	+2	-1	0	+2	-1	-1	0	0
242	Reviewing design storm return periods in the light of new weather information	Research	Regional network	+1	0	0	-1	+2	+1	0	0	0	0	+1	+2

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
243	Stabilize the slope with soil cement	Prevention	Object - stretch	+3	+2	0	-2	+1	+2	-1	-1	-3	-3	0	0
244	Underpinning to stengthening the columns	Upgrade / retrofitting / new construction	Object	+2	+2	0	-3	+1	+2	0	0	0	0	0	0

Table 66: Assessment of measures for Loss of pavement integrity – Cracking, rutting, embrittlement and Decrease in skid resistance on pavements from migration of liquid bitumen (see chapter 4.1.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
415	Access restriction	Traffic management	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
416	Anti-oxidation additives	Research	National network	+1	0	0	0	0	+2	0	0	0	+1	0	+2
417	Cold mill and overlay, thin surface patches	Corrective maintenance and replacement	Stretch	-1	+1	0	-1	0	0	0	0	0	-1	0	+2
418	Harvesting of heat energy from the pavement	Research	Object - stretch	+1	+1	0	0	0	+2	+2	0	0	+1	0	+2
419	High albedo pavements, heat shield pavements, water retention pavements	Research	Stretch - network	+1	+1	0	-1	0	+2	0	0	0	+1	0	+1
420	Keep construction records	Monitoring and prediction	Stretch - network	0	0	0	0	0	0	0	0	0	0	0	0
421	Modal shift	Traffic management	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
422	Placing warning signs	Traffic management	Stretch - network	0	+2	0	-1	0	+2	-2	0	0	+1	0	+2
423	Prepare contingency / emergency plans	Pro-active attitude	Stretch - network	0	+2	0	0	0	+2	-2	0	0	+1	0	+2
424	Preventive information	Research	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
425	Real time traffic information	Traffic management	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
426	Real time weather and traffic forecast	Research	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
427	Replace by more temperature resilient material	Upgrade / retrofitting / new construction	Stretch - network	+1	+1	0	0	0	+2	0	0	0	+1	0	+1
428	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+1	+1	-1	+1	+2
429	Revised standards for materials in surface courses	Prevention	National network	+1	+1	0	0	0	+2	0	0	0	+1	0	+1
430	Treat with hot fine aggregate	Corrective maintenance and replacement	Stretch	-1	+1	0	-1	0	0	0	0	0	-1	0	+2
519	Cold mill and overlay, thin surface patches	Corrective maintenance and replacement	Stretch	-1	+1	0	-1	0	0	0	0	0	-1	0	+2
528	Speed limits	Traffic management	Stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
544	Alternative mixtures for bituminous pavements and surface courses	Research	Stretch	+1	0	0	-1	0	+2	0	0	0	+1	0	+2
547	Restrict working in high temperatures	Prevention	Stretch	+1	0	+1	-1	0	0	0	0	0	+1	0	+1
550	Working during the night	Prevention	Stretch	+1	0	+1	-1	0	0	0	0	0	+1	0	-1

Table 67: Assessment of measures for Loss of pavement integrity – Curling and warping, slab cracking (JRC and URC), punch-out (CRCP), slab faulting (JRC and URC), compression failures, damage at terminal joints (CRCP and CRCB) and effects of water (see chapter 4.2.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
424	Preventive information	Research	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
472	Appropriate maintenance of joint seals to prevent clogging of joints	Preventive maintenance and replacement	National network	+1	0	0	+1	0	0	0	0	0	0	0	0
473	Harvesting of heat energy from the pavement	Research	Object	+1	+1	0	0	0	+2	+2	0	0	+1	0	+2
474	Heat resistant concrete fixings	Research	Object	+1	0	+1	0	0	+2	0	0	0	0	0	0
476	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+1	+1	-1	+1	+2
477	Revised standards for heat resilient pavements, including effects of dark surface courses, joint width in JCP, terminal joint design in CRCP	Prevention	National network	+1	0	+1	0	0	+2	0	0	0	+1	0	0
478	Upgrade joint seal composition	Prevention	National network	+1	0	+1	0	0	+2	0	0	0	+1	0	0
479	Use a low coefficient of expansion coarse aggregates in the mixture	Prevention	National network	+1	0	+1	0	0	+2	0	0	0	+1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
545	Alternative mixtures for concrete pavements	Research	Stretch	+1	0	0	-1	0	+2	0	0	0	+1	0	+2
546	Modify the concrete mixture to ensure adequate workability and curing time	Prevention	Stretch	+1	0	0	-1	0	+2	0	0	0	+1	0	+2
548	Restrict working in high temperatures	Prevention	Stretch	+1	0	+1	-1	0	0	0	0	0	+1	0	+1
549	Restrict concrete paving during periods of heavy rain	Prevention	Stretch	+1	0	+1	-1	0	0	0	0	0	+1	0	+1
551	Working during the night	Prevention	Stretch	+1	0	+1	-1	0	0	0	0	0	+1	0	-1

Table 68: Assessment of measures for Loss of driving ability in case of asphalt overlay – Decrease in skid resistance on pavements from migration of liquid bitumen (see chapter 4.2.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
518	Anti-oxidation additives	Research	National network	+1	0	0	0	0	+2	0	0	0	+1	0	+2
519	Cold mill and overlay, thin surface patches	Corrective maintenance and replacement	Stretch	-1	+1	0	-1	0	0	0	0	0	-1	0	+2
520	Harvesting of heat energy from the pavement	Research	Object - stretch	0	+2	0	0	+1	+2	+2	0	0	+1	0	+2
521	High albedo pavements, heat shield pavements, water retention pavements	Research	Stretch - network	+1	+1	0	-1	0	+2	0	0	0	+1	0	+1
522	Placing warning signs	Traffic management	Stretch - network	0	+2	0	-1	0	+2	-2	0	0	+1	0	+2
523	Prepare contingency / emergency plans	Pro-active attitude	Stretch - network	0	+2	0	0	0	+2	-2	0	0	+1	0	+2
524	Real time traffic information	Traffic management	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
525	Replace by more temperature resilient material	Upgrade / retrofitting / new construction	Stretch - network	+1	+1	0	0	0	+2	0	0	0	+1	0	+1
526	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+2	0	-1	-1	+1

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety. Health & Equity
527	Revised standards for materials in surface courses	Prevention	National network	+1	+1	0	0	0	+2	0	0	0	+1	0	+1
528	Speed limits	Traffic management	Stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
529	Treat with hot fine aggregate	Corrective maintenance and replacement	Stretch	-1	+1	0	-1	0	0	0	0	0	-1	0	+2

Table 69: Assessment of measures for cracking due to weakening of the road base by thaw (see chapter 4.3.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
359	Access restriction	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
360	Appropriate maintenance of cracked pavements, structural measures for underlying causes	Preventive maintenance and replacement	Stretch - network	0	0	0	0	0	0	0	0	0	0	0	0
361	Appropriate maintenance of joint seals, structural measures for underlying causes	Preventive maintenance and replacement	Stretch - network	0	0	0	0	0	0	0	0	0	0	0	0
362	Full depth patches	Corrective maintenance and replacement	Object	0	0	0	0	0	0	0	0	0	-1	0	0
363	In situ strengthening of granular (sub)bases and subgrade soils, using articificial or natural cements	Research	Stretch	+1	0	+1	-2	0	+2	0	0	0	0	0	0
364	Increase the thickness of structural layers	Upgrade / retrofitting / new construction	Object - stretch	+1	0	+1	-1	0	+2	0	0	0	0	0	0
365	Keeping the road drainage in good condition	Preventive maintenance and replacement	Regional network	0	0	0	0	0	0	0	0	0	0	0	0
366	Modal shift	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
367	Monitoring to detect potential problem areas, establish cause-impact relationships; maintain specific construction and maintenance records	Monitoring and prediction	Stretch	0	0	0	0	0	0	0	0	0	+1	0	0

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
368	Prevention of reflection cracking by fibre reinforcement or dedicated interface layers	Upgrade / retrofitting / new construction	Stretch - network	+1	0	+1	-1	0	+2	0	0	0	0	0	0
369	Preventive information	Research	Object - stretch - network	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
370	Real time traffic information	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
371	Real time weather and traffic forecast	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
372	Rerouting and guidance	Traffic management	Stretch	-1	0	-1	+2	-1	+2	-2	0	0	+1	0	0
373	Rerouting and guidance	Traffic management	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+1	+1	-1	+1	+2
374	Revised standards for binder course, (sub)base and subgrade materials, drainage	Prevention	Object - stretch - network	+1	0	+1	-1	0	+2	0	0	0	+1	0	0

Table 70: Assessment criteria for Traffic Management measures (see chapter 5.2.7)

Nr.	Adaptation measure	Policy	Scale	Qualitative score on criteria					Contribution to sustainability criteria						
				Availability	Safety	Impact on network	Direct cost	Reputation	General / Management	Climate change and Energy	People and Communities	Ecology / Biodiversity	Physical resources	Quality of Life	Safety, Health & Equity
1	Prepare Traffic Management Plans	Prevention	TEN-T - national - regional	+2	+1	+3	-1	+2	+2	+2	+2	0	0	+1	+2
2	Access restriction	Response	Stretch - network	+2	0	-2	+2	-1	+2	+2	+1	0	+1	0	0
3	Carriageway cross-over	Response	Stretch	-2	-1	0	-2	-2	0	0	0	0	+1	+1	+2
4	Construction of (temporary) flood barriers along road	Response	Stretch	+2	+1	+1	-2	+1	0	0	0	0	0	0	+1
5	HGV Storage		Stretch	-3	+3	+2	-3	-3	+1	+2	+1	+1	-1	+1	+2
6	Install sign posts warning for flooding in threatened areas	Prevention	Object - stretch - network	+3	+2	-1	-1	0	0	0	0	0	0	0	0
7	Placing warning signs	Preparation	Stretch - network	0	+2	0	-1	0	+2	-2	0	0	+1	0	+2
8	Lane closure	Response	Stretch	-2	+3	0	-2	-2	0	+1	-1	+1	0	-1	+2
9	Modal shift	Prevention - Response	Regional network	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
10	Real time traffic information	Prevention - Response	Object - stretch - network	+2	+2	+2	-1	+1	+2	0	0	0	0	0	+2
11	Rerouting and guidance	Prevention - Response	TEN-T - national - regional	+2	0	+3	-2	-1	+1	+2	+2	0	-1	-1	+1
12	Speed limits	Prevention - Response	Stretch	+2	+3	0	-1	-1	+1	+2	+1	+1	-1	+1	+2
13	Weight limits	Prevention - Response	Stretch	-2	+2	-2	-1	-2	+1	+2	+1	+1	-1	+1	+2