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Evaluating adaptation options for resilient road infrastructure

Delft, September 2024

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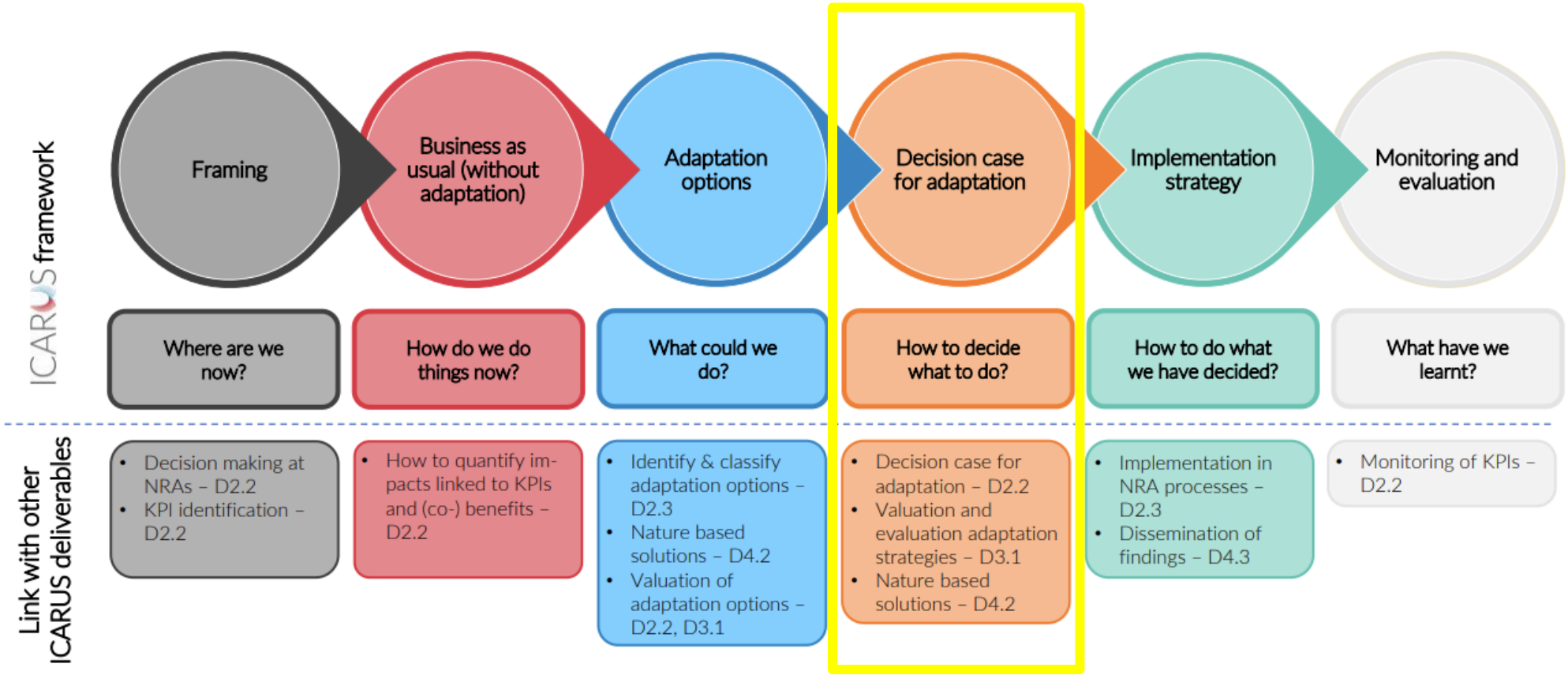
ICARUS Framework



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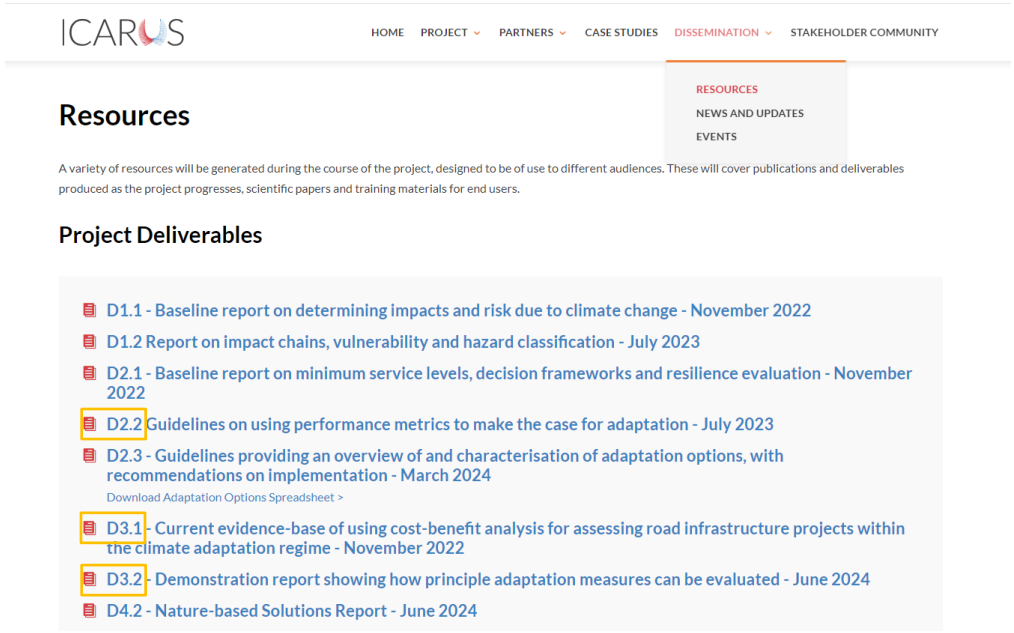
Key learning points

- Evaluation of adaptation options
- Choosing between different adaptation options
- Finding the optimal level of adaptation
- Example of cost and benefits to include in the analysis (specific case)

Resources available

- The resources are available on the ICARUS website:



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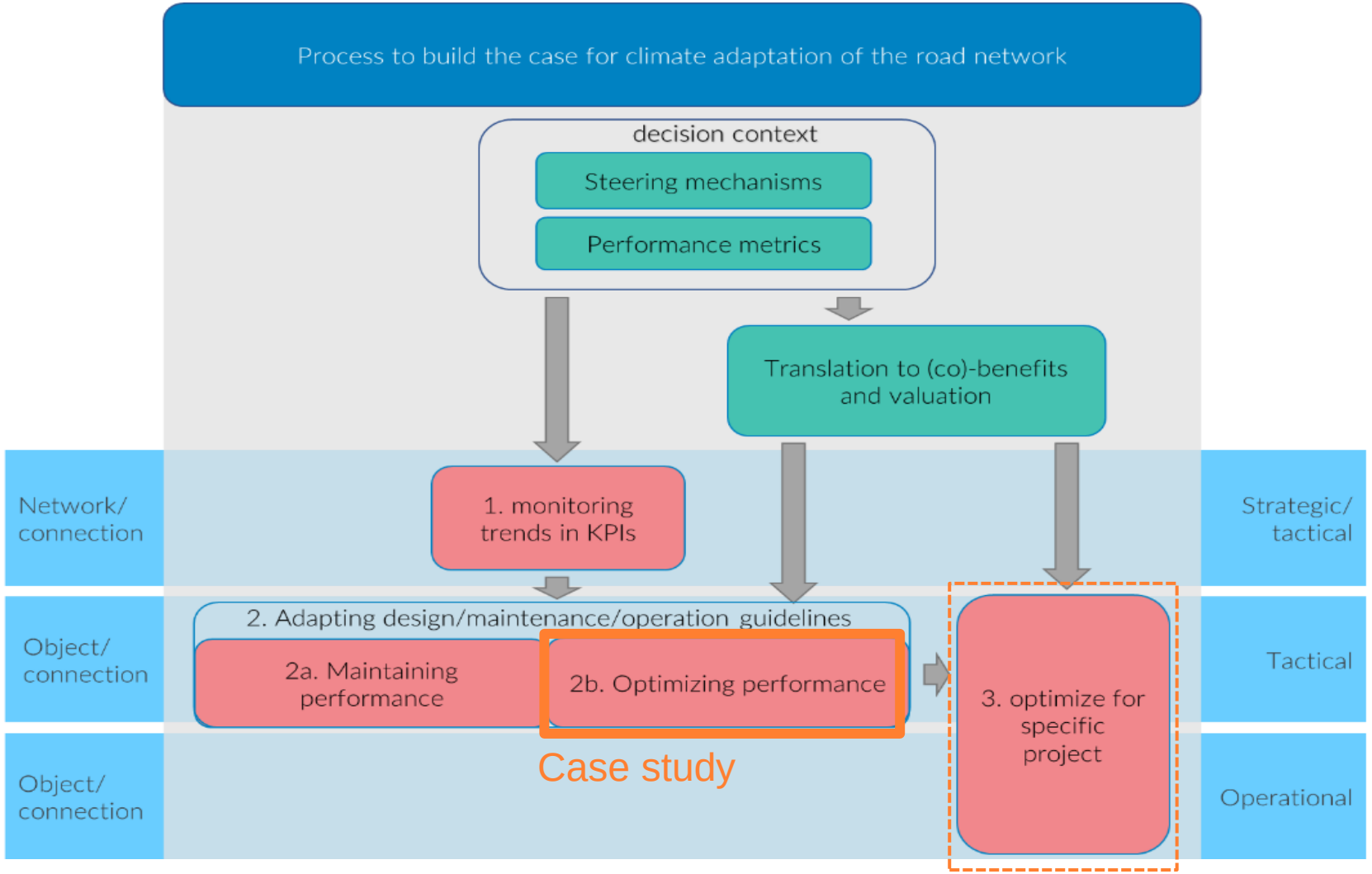
Making the case for climate adaptation



Evaluating adaptation options

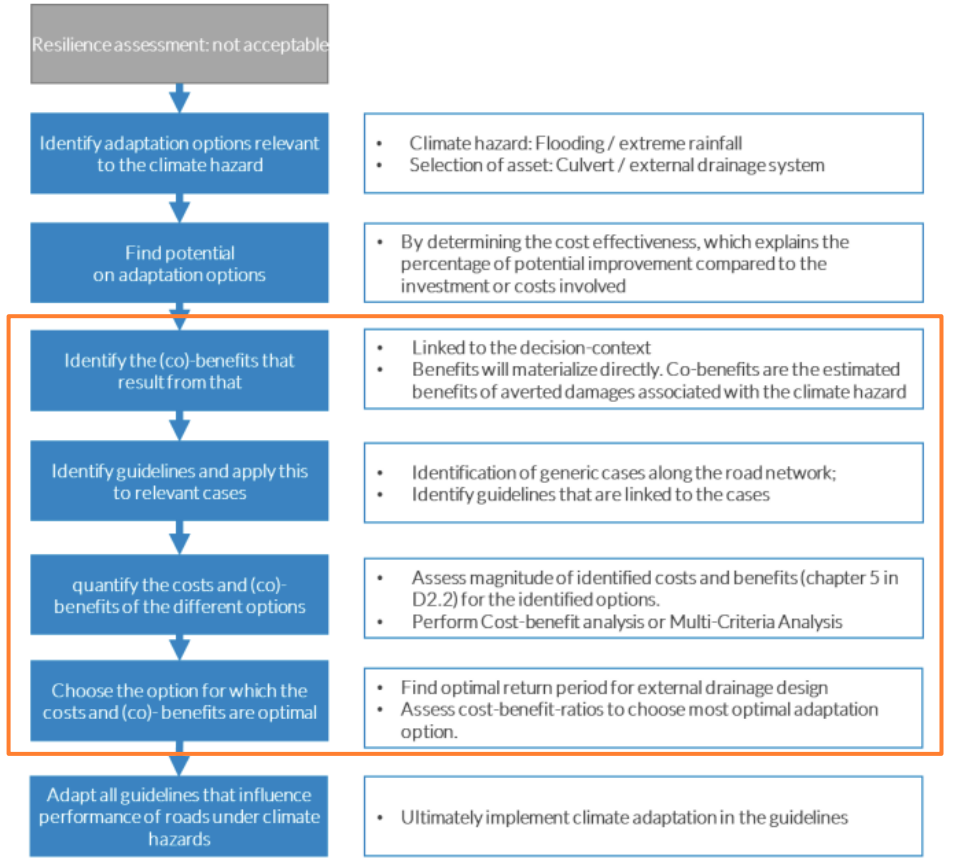
Level of resilience: not acceptable

Credit: Michael Wulff Hansen

Credit: pressefoto.dk

Credit: Chone

Case Study from D3.2



Case introduction - Decision context

Governing decision criteria for NRA

Major highway, 3 lanes. Important connection between the two larger industrial cities. Link to other major roads and highways across the country, thus contributing to the larger road network.

KPI's

- **Availability** measured simply in as the value of travel time
- **Safety** measured simply as the value of yearly fatalities and injuries
- Low maintenance and repair **cost**

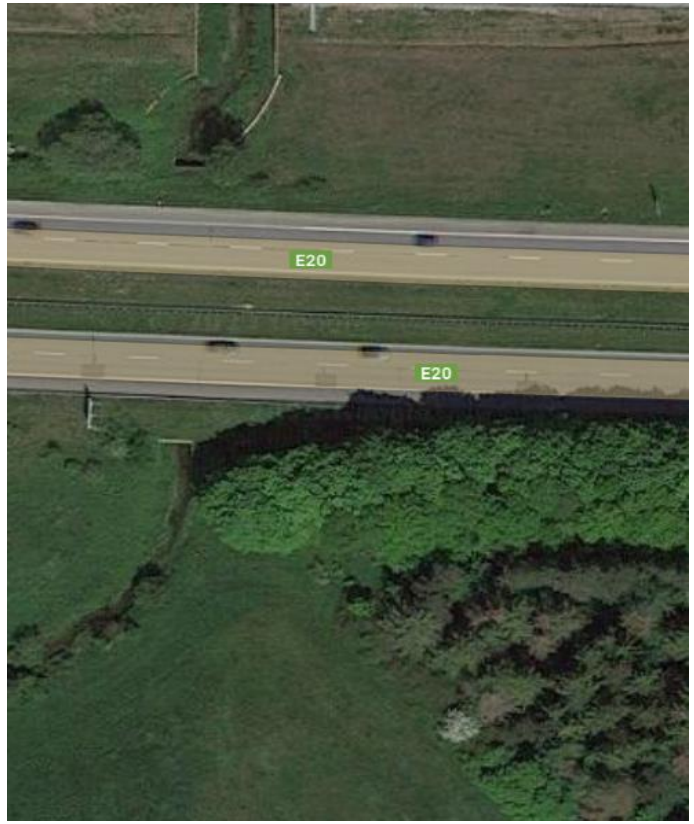
Increased focus on reputation and social awareness, ecosystem services

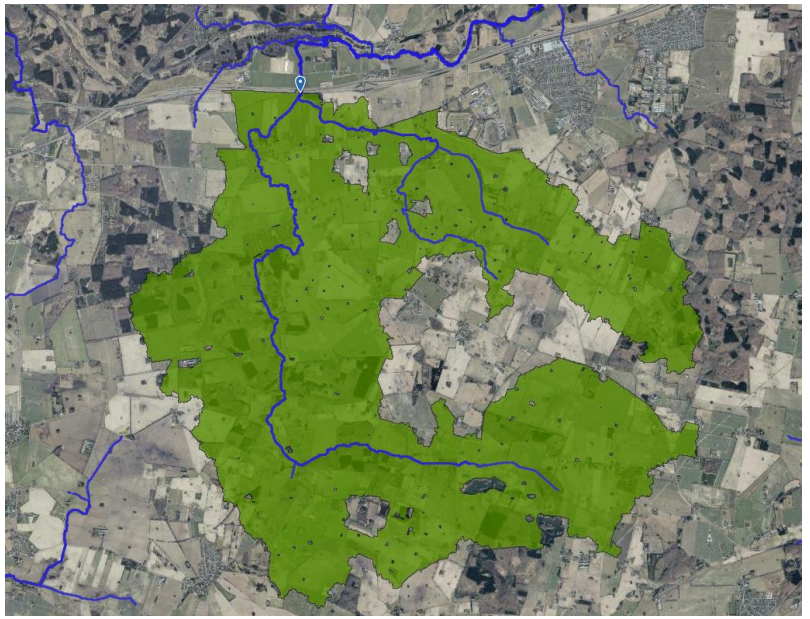
Annual average daily traffic: 76,400	**Average number of injuries**
Average speed: 105 km/h	**- Severely injured:** 7 /year
Average travel time: 3 minutes	**- Minorly injured:** 19 /year
Average number of fatalities: 0.3/year	

Case introduction - The culvert

- **Design Guidelines:**
  - Clear recommendations regarding the internal drainage
  - Vague recommendations regarding the external drainage
- **Culvert**
  - 2m diameter, max flow 7500 L/s
  - 2-year event today

Climate change
Will increase the peak flow in the stream, the capacity of the existing culvert will be exceeded often





The river catchment upstream the culvert is 4500 ha and primarily consists of green fields and forest

What adaptation option should be implemented? What is the optimum level of adaptation?

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Possible damages - The capacity of the culvert is exceeded

10-year event: Water accumulation will increase; two out of three lanes will be highly affected.

Travel time is increased by 110 pct. compared to normal.

The road needs a minor maintenance check afterward

25-year event: All three lanes are heavily impacted by the accumulated water.

Travel time is increased by 200 pct., compared to normal.

The road needs a minor maintenance check afterward

100-year event: The road is completely closed

The brinks around the road will become unstable and pieces of the road will need maintenance work and repair in the aftermath of the event.

Level of resilience: not acceptable

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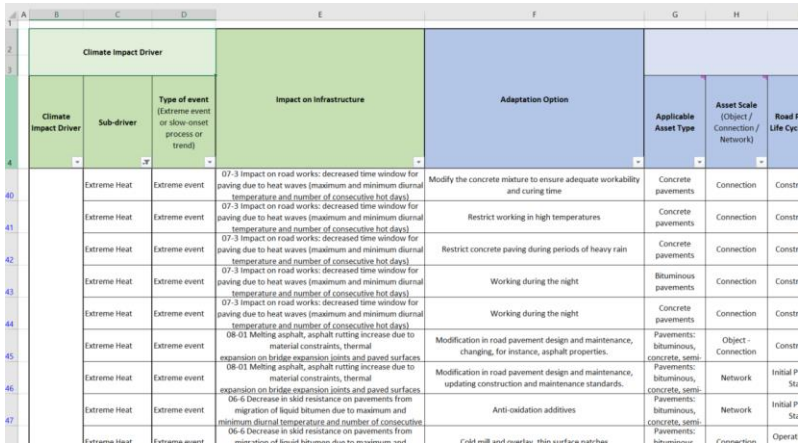
Adaptation? - Outlining options

- Change the drainage capacity
  - *To what level? – Optimization level 1 and 2*
- Using what strategy?
  - *Retention (NbS)*
  - *Conveyance (Increase the size of the culvert)*

Preceding steps

1. Screen for possible adaptation options using ICARUS_D2.3 Adaptation Options tool
2. Perform a cost-effectiveness assessment to identify options for consideration



	Climate Impact Driver			Impact on Infrastructure	Adaptation Option	Applicable Asset Type	Asset Scale (Object / Connection / Network)	
	Climate Impact Driver	Sub-driver	Type of event (Extreme event or slow-onset process or trend)					
40	Extreme Heat	Extreme event		07-3 Impact on road works: decreased time window for paving due to heat waves (maximum and minimum diurnal temperature and number of consecutive hot days)	Modify the concrete mixture to ensure adequate workability and curing time	Concrete pavements	Connection	
41	Extreme Heat	Extreme event		07-3 Impact on road works: decreased time window for paving due to heat waves (maximum and minimum diurnal temperature and number of consecutive hot days)	Restrict working in high temperatures	Concrete pavements	Connection	
42	Extreme Heat	Extreme event		07-3 Impact on road works: decreased time window for paving due to heat waves (maximum and minimum diurnal temperature and number of consecutive hot days)	Restrict concrete paving during periods of heavy rain	Concrete pavements	Connection	
43	Extreme Heat	Extreme event		07-3 Impact on road works: decreased time window for paving due to heat waves (maximum and minimum diurnal temperature and number of consecutive hot days)	Working during the night	Bituminous pavements	Connection	
44	Extreme Heat	Extreme event		07-3 Impact on road works: decreased time window for paving due to heat waves (maximum and minimum diurnal temperature and number of consecutive hot days)	Working during the night	Concrete pavements	Connection	
45	Extreme Heat	Extreme event		08-01 Melting asphalt, asphalt rutting increase due to material constraints, thermal expansion on bridge expansion joints and paved surfaces	Modification in road pavement design and maintenance, changing, for instance, asphalt properties.	Pavements: bituminous, concrete, semi-	Object - Connection	
46	Extreme Heat	Extreme event		08-01 Melting asphalt, asphalt rutting increase due to material constraints, thermal expansion on bridge expansion joints and paved surfaces	Modification in road pavement design and maintenance, updating construction and maintenance standards.	Pavements: bituminous, concrete, semi-	Network	
47	Extreme Heat	Extreme event		06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of consecutive	Anti-oxidation additives	Pavements: bituminous, concrete, semi-	Network	
	Extreme Heat	Extreme event		06-6 Decrease in skid resistance on pavements from	Cold mill and overlay, thin surface patches	Pavements:	Connection	

Adaptation? - Outlining options

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Optimization level 1			
		Increase size of culvert	**Nature-based solution**
Benefits	Availability	*Improved compared to reference scenario*	*Improved compared to reference scenario*
	Safety	*Improved compared to reference scenario*	*Improved compared to reference scenario*
	Costs associated with repair and maintenance after flooding	*Reduction compared to reference scenario*	*Reduction compared reference scenario*
Co-benefits	Increase in co-benefits associated with ecosystem services	*No co-benefits associated with increasing the culvert*	*Co-benefits associated with applying nature-based solutions.*
Optimization level 2			
		Increase size of culvert	**Nature-based solution**
Benefits	Availability	*Significantly improved compared to reference scenario*	*Significantly improved compared to references scenario*
	Safety	*Significantly improved compared to reference scenario*	*Significantly improved compared to reference scenario*
	Costs associated with repair and maintenance after flooding	*Reduction compared to reference scenario*	*Reduction compared to reference scenario*
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Optimization level 2

		Increase size of culvert	Nature-based solution
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	Safety	*Significantly improved compared to reference scenario*	*Significantly improved compared to reference scenario*
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Benefits - Estimation method

Benefits of averted decrease in availability and safety

Estimation method:

- Flood simulations (water level on the road)
- Traffic model/ data on changes in availability and safety (due to the water on the road and/or closed lanes)
- Unit prices for injuries and delays

Benefits of averting repair and maintenance costs:

- Adaptation solutions implemented for either Optimization Level 1 and 2 will reduce the costs for repair and maintenance for extreme events.

Benefits - Estimation method

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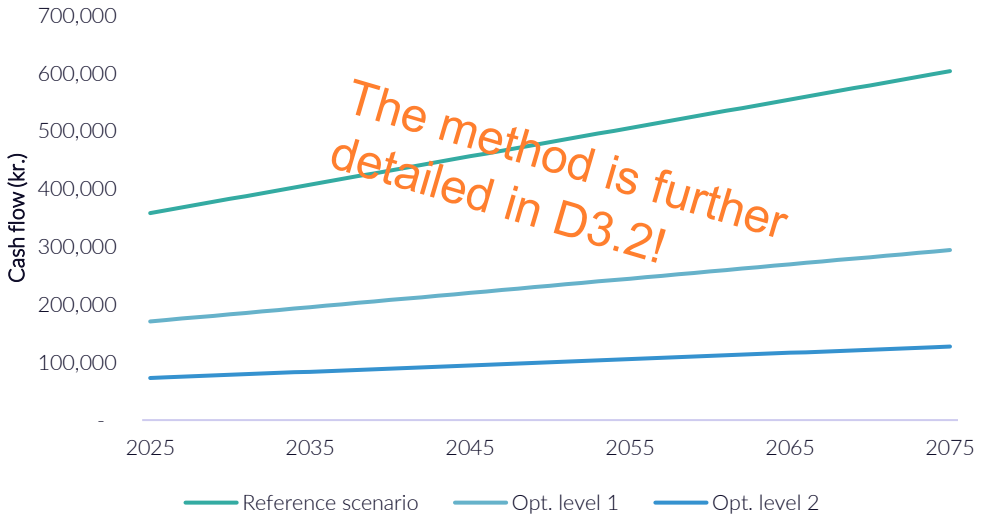
Expected annual damage
Damage is associated with a probability. The probability is changing due to climate change.

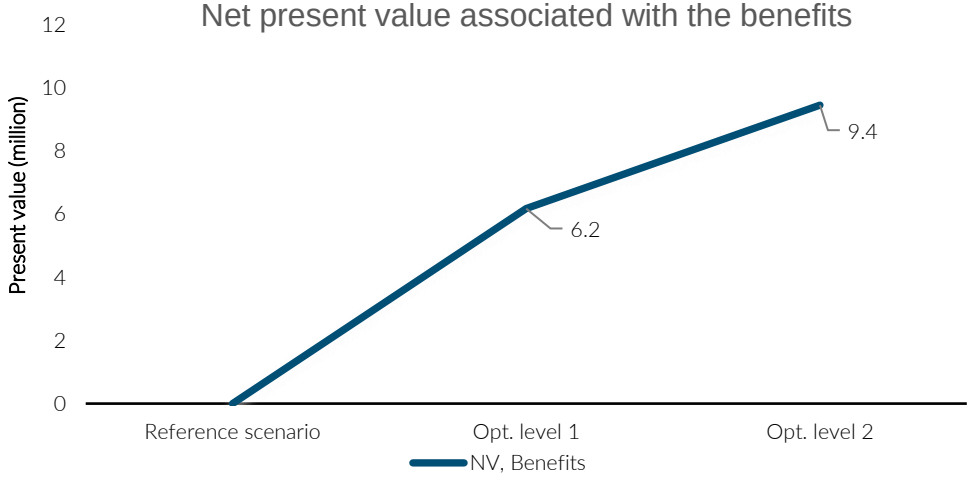
Discounting
The present value of a payment that is to happen in the future is lower than the present value of a payment you receive today.

Net present value
The two things brought together and summarized to *one* number.

Expected annual damage for the three scenarios

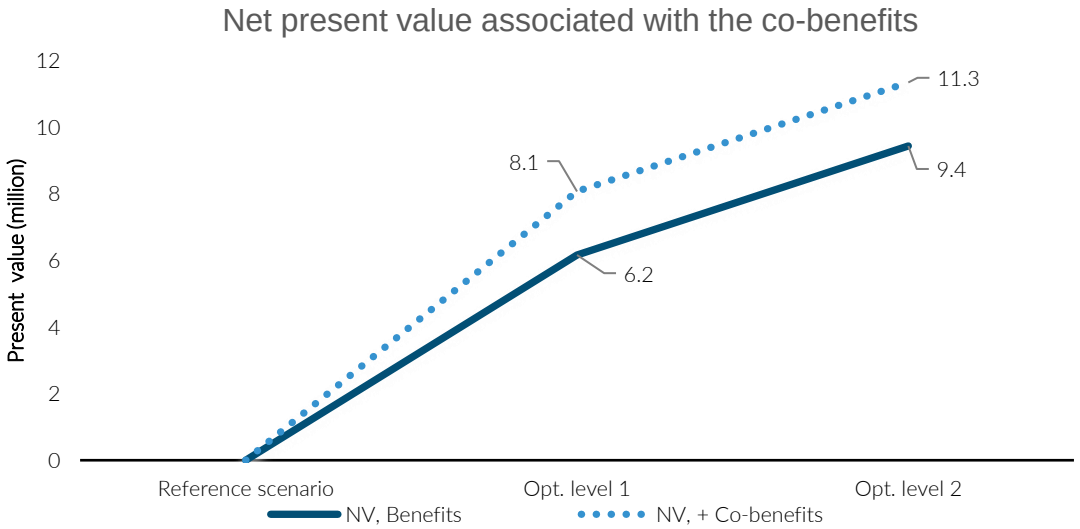


Net present value associated with the benefits



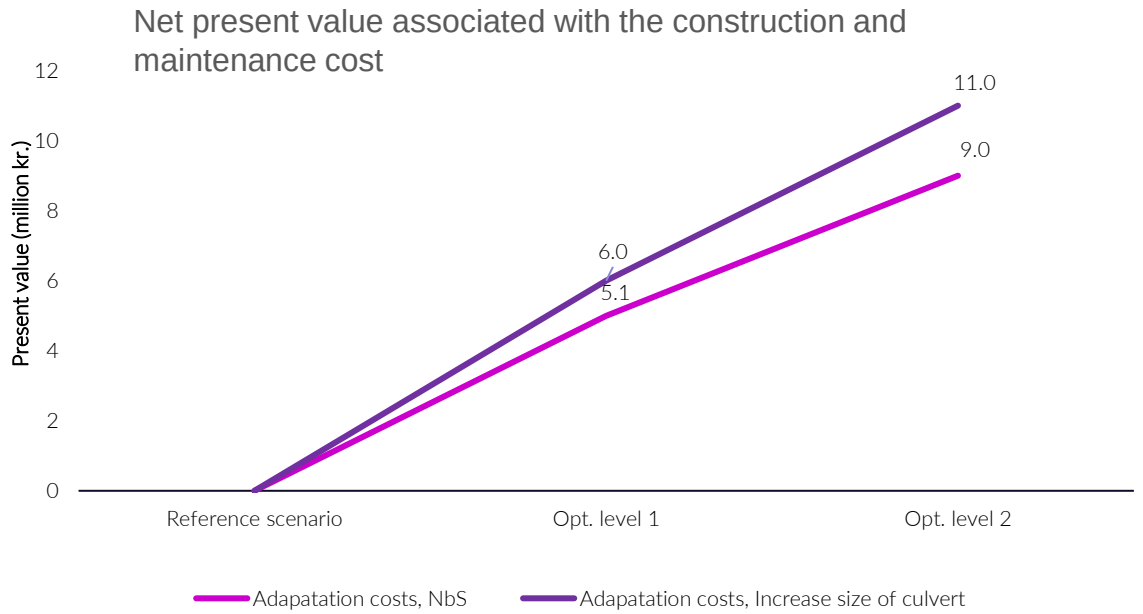
Co-benefits - Recreational value of the Nature-based Solution

- The NbS will be located upstream, detaining water and reducing the peak flow in the existing culvert.
- It has the potential to provide additional value in the form of increased recreational value for any visitors.
- Recreational value: **26.000 kr./year/ha.** for the specific region. Based on numbers for the national environmental agency (travel cost method)
- It is assumed that the value is the same for both optimization level 1 and 2.



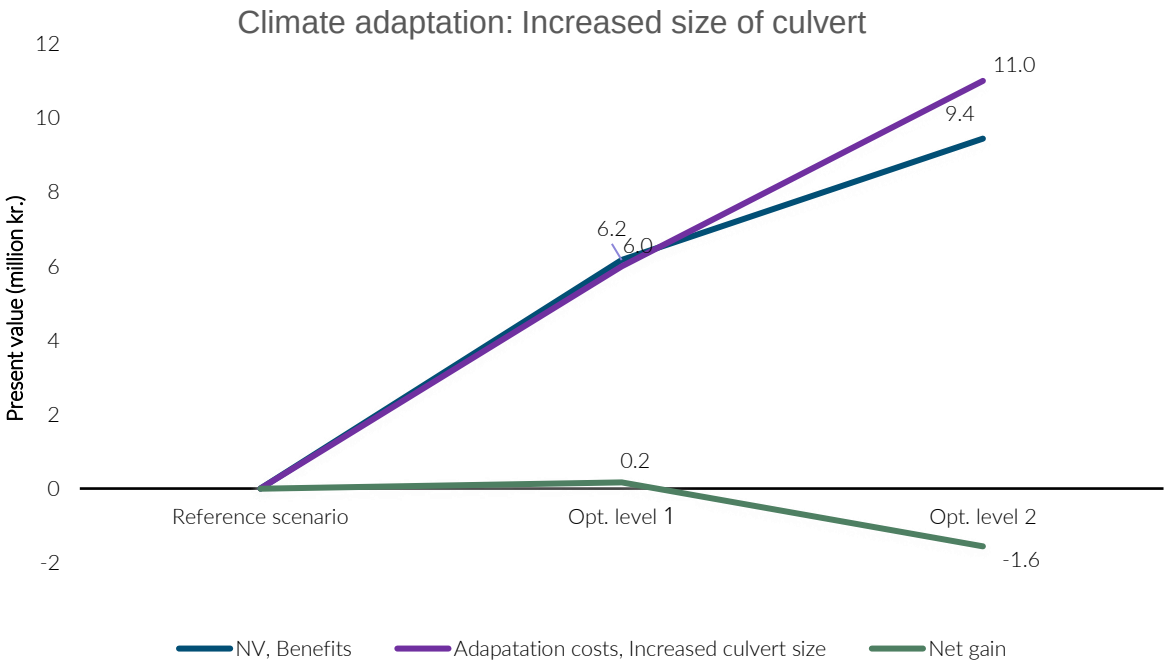
Cost of adaptation - Construction + maintenance

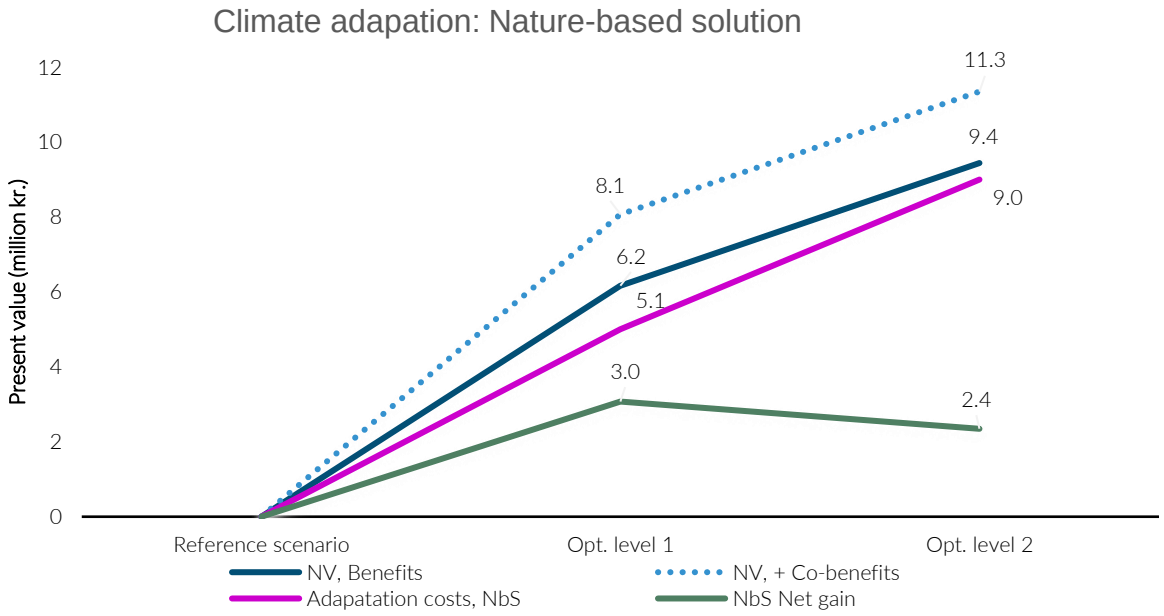
- Cost of increasing the culvert
- Cost of establishing retention volume and acquiring the land
- Maintenance costs for both solutions
- Discounting
- Net present value



Net present value, DKK	**Optimization level 1**	**Optimization level 2**
Increased size of culvert	6 million DKK	11 million DKK
Nature-based solution	5 million DKK	9 million DKK

Choosing the best option - by bringing everything together





In this case, the optimal solution is an NbS with optimization level 1

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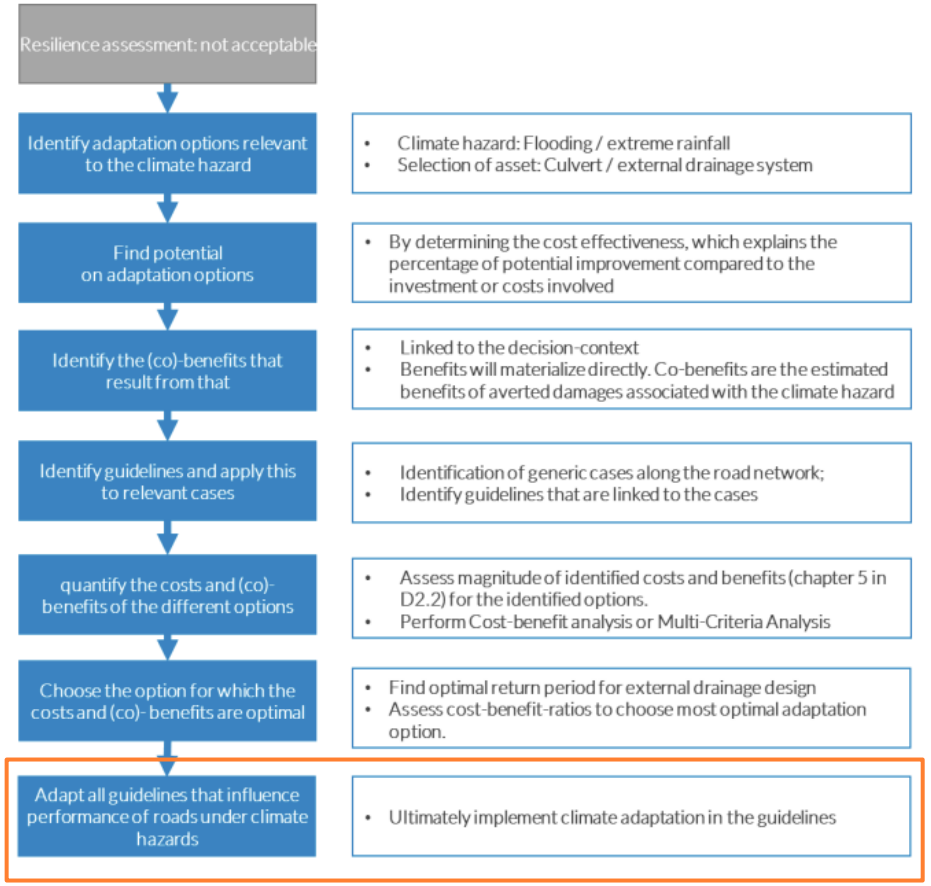
Adapting guidelines?

Lessons learned from project implementation could lead to adaptation of guidelines that influence asset performance

Case study:
Guidelines for consideration of external drainage for major roads adapted to consider climate change



Evaluation of Adaptation Options

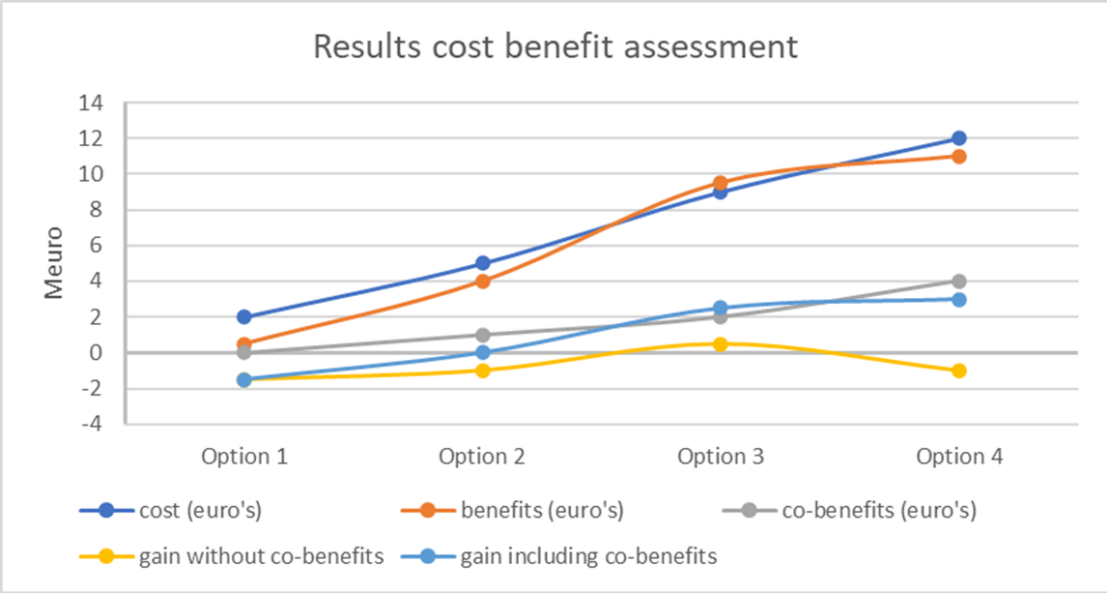
1. Based on the priorities of your organisation defined in the previous exercise, what KPIs are relevant for your infrastructure network and chosen adaptation options?

2. Prepare a list of benefits and co-benefits for each of your chosen adaptation options.

3. Based on these benefits/co-benefits, what data collection and analyses (and/or expert input) is needed to evaluate your chosen adaptation options?

Evaluation of Adaptation Options

4. A CBA has been prepared for four adaptation options to be implemented within your infrastructure network. What option would you choose? Please consider your decision context!



	Option 1	Option 2	Option 3	Option 4
Cost (M euro's)	2	5	9	12
Benefits (M euro's)	0,5	4	9,5	11
Co-benefits (M euro's)	0	1	2	4
Benefits-cost (M euro's)	-1,5	-1	0,5	-1
Co-benefits cost (M euro's)	-1,5	0	2,5	3

5. Please reflect on your organization's implementation process. What are your thoughts on implementing the ICARUS approach for evaluation of adaptation options in your organization?

Discussion

- Any questions?

Summary – Evaluation of Adaptation

- Decision criteria needs to be in place
  - KPI: Safety, availability, maintenance cost including repair
  - Policy: social and ecological awareness
- Data needed:
  - Numbers on safety and availability today
  - Knowledge on climate change (factors of change)
  - Flood modelling (rainfall events -> impacts)
  - Value of delay and injuries
  - Recreational value of green spaces
  - Discount rate

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Recommendations for evaluation

- Consider and compare multiple adaptation options
- Consider and compare multiple optimisation levels
- Account for uncertainty!
- Carefully consider the discount rate applied in the CBA

    Most countries have national guidelines that should be adhered to

Adaptation Options Spreadsheet

Climate Impact Driver				Adaptation Option	Adaptation Option Characteristics								Evaluation Criteria						
													Benefits and Co-Benefits						
Climate Impact Driver	Sub-driver	Type of event (Extreme event or slow-onset process or trend)	Impact on Infrastructure		Applicable Asset Type	Asset Scale (Object / Connection / Network)	Road Project Life Cycle Stage	Impact Chain Stage 1. Hazard 2. Exposure 3. Vulnerability 4. Impact	Disaster Risk Management Cycle Stage Prevention Preparedness Response Recovery	Short/ Long Term Solution	Is the climate impact driver addressed?	Is this a Nature-Based Solution?	Availability -1: decreased network availability 0: No change +1: Increased network availability	Durability -1: decreased asset durability 0: No change +1: Increased asset durability	Impact on Safety -1: Increase in no. of collisions 0: No change +1: Decrease in no. of collisions	Impact on Health -1 : Negative 0: No change +1: Positive	EcoSystem Services -1: Decrease in level of greening of area 0: No change +1: Increase in level of greening of area	Water Quality -1: Deterioration in water quality 0: No change +1: Improvement in water quality	Climate: Embodied Carbon -1: Increase in carbon emissions 0: No change +1: Decrease in carbon emissions
Heat and Cold	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Harvesting of heat energy from the pavement	Pavements: bituminous, concrete, semi-	Object - Connection	Initial Proposal Stage	3. Vulnerability	Prevention	Short term (operational and tactical)	Yes	no	1	1	0	0	0	0	0
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	High albedo pavements, heat shield pavements, water retention pavements	Pavements: bituminous, concrete, semi-	Connection - Network	Initial Proposal Stage	3. Vulnerability	Prevention	Short term (operational and tactical)	Yes	no	1	1	1	0	0	0	0
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Placing warning signs	Pavements: bituminous, concrete, semi-	Connection - Network	Operation and Maintenance	2. Exposure	Preparedness	Short term (operational and tactical)	No	no	0	0	1	0	0	0	0
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Prepare contingency / emergency plans	Pavements: bituminous, semi-rigid	Connection - Network	Planning and Detailed Design	2. Exposure	Prevention	Long term (tactical and strategic)	No	no	0	0	1	0	0	0	0
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Real time traffic information	Pavements: bituminous, concrete, semi-	Object - Connection - Network	Operation and Maintenance	2. Exposure	Response	Short term (operational and tactical)	No	no	1	0	1	0	0	0	0
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Replace by more temperature resilient material	Pavements: bituminous, concrete, semi-	Connection - Network	Construction	3. Vulnerability	Preparedness	Short term (operational and tactical)	Yes	no	1	1	1	0	0	0	0
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Rerouting and guidance	Bituminous pavements	Network	Operation and Maintenance	2. Exposure	Recovery	Short term (operational and tactical)	No	no	-1	0	1	0	0	0	0
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Revised standards for materials in surface courses	Pavements: bituminous, concrete, semi-	Network	Initial Proposal Stage	3. Vulnerability	Preparedness	Long term (tactical and strategic)	Yes	no	1	1	1	0	0	0	0
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Speed limits	Pavements: bituminous, concrete, semi-	Connection - Network	Operation and Maintenance	2. Exposure	Response	Short term (operational and tactical)	No	no	-1	0	1	0	0	0	1
	Extreme Heat	Extreme event	06-6 Decrease in skid resistance on pavements from migration of liquid bitumen due to maximum and minimum diurnal temperature and number of	Treat with hot fine aggregate	Pavements: bituminous, concrete, semi-	Connection	Operation and Maintenance	3. Vulnerability	Recovery	Short term (operational and tactical)	Yes	no	1	1	1	0	0	0	0
	Cold Spell	Extreme event	Road surfacing may have a more brittle structure due to increased number of frost/thaw days. However cost savings may be made due to a	Alternative mixtures for bituminous pavements and surface courses to reduce brittleness.	Bituminous pavements	Connection	Initial Proposal Stage	3. Vulnerability	Preparedness	Short term (operational and tactical)	Yes	no	1	1	0	0	0	0	1
	Frost	Extreme event	04-4 Instability / subsidence of roads by thawing of permafrost	Access restriction	All road infrastructure	Object - Connection - Network	Operation and Maintenance	2. Exposure	Response	Short term (operational and tactical)	No	no	-1	0	0	0	0	0	0
	Frost	Extreme event	04-4 Instability / subsidence of roads by thawing of permafrost	Artificial cooling and/or extracting heat from the embankment	Pavements: bituminous, concrete, semi-	Object - Connection	Planning and Detailed Design	3. Vulnerability	Prevention	Short term (operational and tactical)	Yes	no	1	1	1	0	0	0	0
	Frost	Extreme event	04-4 Instability / subsidence of roads by thawing of permafrost	Designing and repairing frost damaged roads in accordance with ROADEX guidelines for roads suffering from spring thaw weakening	Pavements: bituminous, concrete, semi-	Object - Connection	Operation and Maintenance	3. Vulnerability	Preparedness	Short term (operational and tactical)	Yes	no	1	1	0	0	0	0	0
	Frost	Extreme event	04-4 Instability / subsidence of roads by thawing of permafrost	Designing and repairing frost damaged roads in accordance with ROADEX guidelines for roads suffering from spring thaw weakening	Pavements: bituminous, concrete, semi-	Object - Connection	Planning and Detailed Design	3. Vulnerability	Prevention	Short term (operational and tactical)	Yes	no	1	1	0	0	0	0	0
	Frost	Extreme event	04-4 Instability / subsidence of roads by thawing of permafrost	Excavating the frozen icy material and replacing it with thaw-stable fill	Pavements: bituminous, concrete, semi-	Object - Connection	Operation and Maintenance	3. Vulnerability	Response	Short term (operational and tactical)	Yes	no	1	1	0	0	0	0	0
	Frost	Extreme event	04-4 Instability / subsidence of roads by thawing of permafrost	Increase the thickness of structural layers	Pavements: bituminous, concrete, semi-	Object - Connection	Construction	3. Vulnerability	Preparedness	Short term (operational and tactical)	Yes	no	1	1	1	0	0	0	0
	Frost	Extreme event	04-4 Instability / subsidence of roads by thawing of permafrost	Increase width of lane for removal of snow	Pavements: bituminous, concrete, semi-	Network	Operation and Maintenance	4. Impact	Response	Short term (operational and tactical)	Yes	no	1	0	1	0	0	0	0

Examples of Adaptation Options (from D3.2)

Adaptation option	Climate impact driver	Lifetime	Cost	Benefits	Co-benefits
Improve forest management in the catchment area	Wet and Dry – River Flood (Extreme Event)	• **Forest management**: continuous process • **Tree growth**: variable • **Forest**: can be maintained long term	• **Land cost**: vary by location • **Tree planting**: low cost, but benefits take time • **Tree failure**: high in early stages. Potential replanting needed • **Forest management**: low	• Ecosystem services • Accessibility • Job opportunities • Safety • Climate change	• Potentially negative embodied carbon • Positive impact on biodiversity • Recreational • Coppicing for biofuel or forest products • Potential increase in land value
Resize drainage systems to meet threats	Wet and Dry – Heavy Precipitation and Pluvial Flood (Extreme Event)	• **Design life**: 50-120 years • **Maintenance**: regular	• Depends on conditions	• Safety • Durability • Accessibility	• Positive impact on biodiversity • Improved road user experience • Stabilized flow of water into streams
Moving of verges	Wet and Dry – Wildfire Conditions (Extreme Event)	• 1-3 times per year	• Low	• Safety • Climate change • Ecosystems	• Improved aesthetics • Positive impact on biodiversity
Changing the land use in the proximity of the road to other vegetation	Wet and Dry – Wildfire Conditions (Extreme Event)	• Ongoing process	• **Removing dead material/leaf litter**: modest • **Vegetation replacement**: high	• Safety • Ecosystem • Durability	• Positive impact on biodiversity • Drought resilience
Protection of wind exposed road sections and assets with planted forests and other vegetation	Wind - Tropical Cyclone (Extreme Event)	• Regular maintenance is required throughout the lifecycle including pruning trees and clearing roads of fallen branches	• Variable	• Climate Change • Safety • Accessibility • Ecosystem Services	• Climate Change mitigation • Reduction of storm surges' strength • Improvement in the distribution of temperature and moisture along road sections