FEHRL

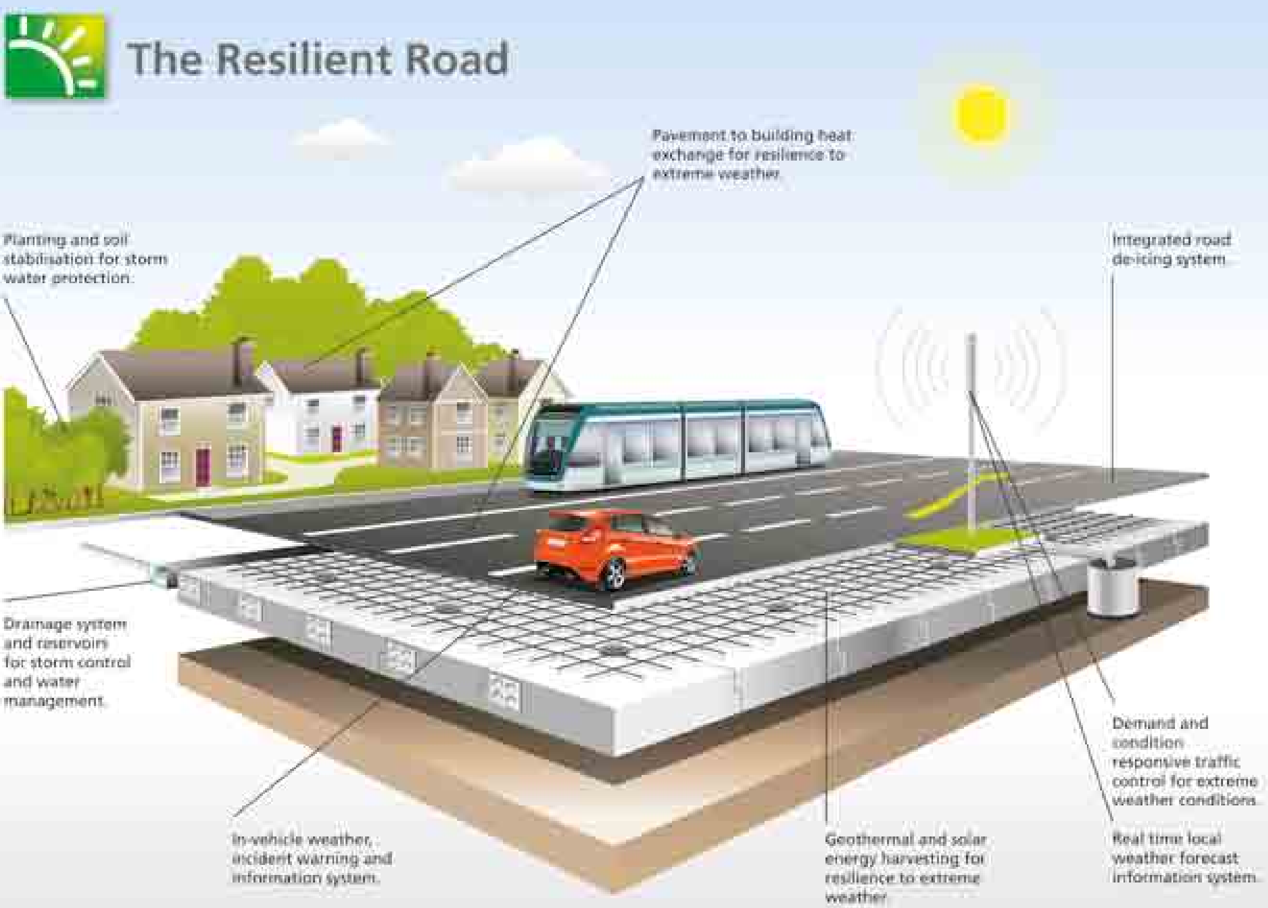
THE RESILIENT ROAD

A ROADMAP FOR RESEARCH 2017 UPDATE

AN ELEMENT OF THE FOREVER OPEN ROAD PROGRAMME

APRIL 2017

FOREVER OPEN ROAD
Redefining Road Transport for the 21st Century
FEHRL's Flagship Programme



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EXECUTIVE SUMMARY

The Forum of European Highway Research Laboratories (FEHRL) initiated the Forever Open Road (FOR) Programme as the core of its Strategic European Road Research Programme V (SERRP V) which ran from 2011 to 2016. The FOR Programme works towards a next generation of advanced and affordable, smarter, connected and resilient roads that can be adopted both for maintaining the existing network and building new roads. This will enable future road operators to adopt emerging innovations, whilst overcoming the increasing constraints on capacity, sustainability, reliability and integration. It will also enable the whole socio-technical system (e.g. road operators/managers/stakeholders) to adapt for climate change and extreme weather events and prevent/minimise social and economic costs. FOR will also contribute substantially to the way the road transport sector addresses societal challenges.

The next generation of roads will require high levels of adaptation, automation and resilience. These three elements will define the next generation of road as follows:

- **The Adaptable Road:** focusing on ways to allow road operators to respond in a flexible manner to changes in road users demands and constraints.
- **The Automated Road:** focusing on the full integration of intelligent communication technology applications between the user, the vehicle, traffic management services and the road operations.
- **The Resilient Road:** focusing on ensuring service levels are maintained under extreme weather conditions and man-made events.

The Resilient Road Roadmap was originally published in January 2013, and described the Resilient Road Element of the FOR Programme. This document presents an update on the original document, measuring progress against the original milestones and reviewing the technical elements and revising as required. This document has been developed through a series of workshops with technical input from experts and practitioners from FEHRL and supporting organisations.

An efficient and reliable transport system is essential for society, the transport of goods, employment and leisure. Currently, Europe's transport systems struggle to cope with extreme weather events such as droughts, heavy rain and snow, storms and floods; and climate change is predicted to increase the frequency and severity of extreme weather events.

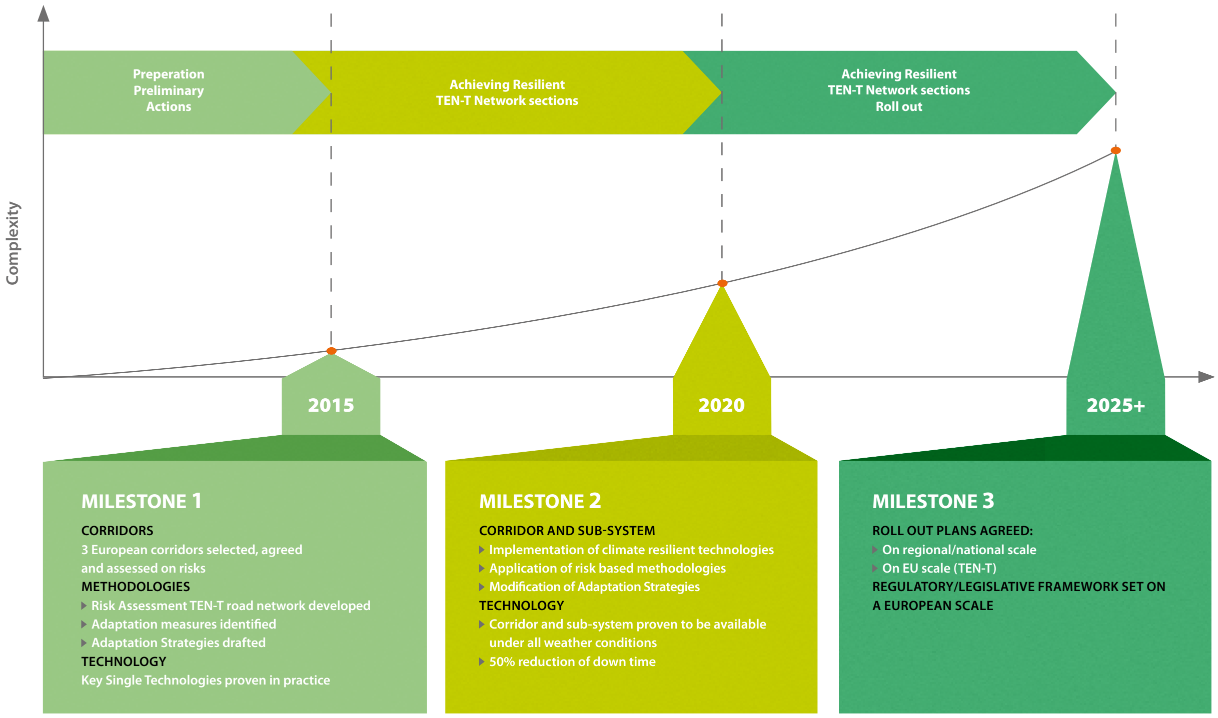
The entire transport infrastructure (road, rail, airports, sea ports and inland waterways) will be significantly impacted by climate change, affecting the way Europe's transport sector plans, designs, constructs and maintains infrastructure in the future.

Equally, the EU Strategy on Adaptation to Climate Change estimated the cost of not adapting to climate change of between €100 to 250 billion, and that every Euro spent on flood protection could save €6 on damage prevention. It is therefore apparent that for a number of strategies, the cost of implementation needs to be considered in the context of the cost of not implementing them.

On the basis that there will be significant impacts from climate change, and considering that all eventualities cannot be catered for, this Roadmap aims to determine how road transport infrastructure should adapt to the inevitable changes, increasing resilience to the potential effects of climate change.

This Roadmap sets out the steps required to maintain and improve the resilience to extreme weather of road transport networks and specifically the key Trans-European Network (TEN-T) road transport network events. Whilst focussing on roads, it will also consider interactions with other modes (complying with FEHRL's new FORx4 programme[1] that was launched since this first roadmap was published).

[1] More details on FORx4 can be found at http://www.foreveropenroad.eu/?m=26.



The Milestone 1 notional targets indicated that three European corridors would be selected, agreed upon and assessed on risk. Whilst there was not a coordinated approach to this, it is known that there were a number of Conference of European Directors of Roads (CEDR) and EC projects that have sought to develop approaches to implement adaptation and mitigation strategies and also embed performance specifications (green procurement) and CO_2 targets into their procurement processes. Specific examples of projects supporting the development of the milestone 1 targets are presented in the document, indicating that the milestone has been achieved overall.

The guiding principles of the FOR Resilient Element are that:
- A reliable transport system is essential to the functioning European society.
- The financial cost of network interruption from extreme weather events is difficult to quantify, but is estimated to be in excess of €15 billion per annum (EWENT Project 2012).
- Climate change will increase the severity and frequency of extreme weather events and thereby lower the reliability and performance of the transport system.
- Man-made events (accidents, vandalism, malicious acts and terrorism) will also lower the resilience of the transport system.
- Appropriate action can mitigate the adverse impacts of climate change.

Given the long life-cycle time of infrastructure, action is needed urgently, at least in some identified vulnerable areas (such as coastal cities, mountainous areas and outermost reaches of the EU such as the Azores, Madeira and Canary Islands). The following headline actions are proposed:
- Define requirements for climate projections.
- Support the harmonisation of climatologic data.
- Develop appraisal tools to assess the economic and social costs of disruptions.
- Identify vulnerabilities on the key European transport networks.
- Identify critical nodes of the infrastructure network, including the supply chain critical points.
- Establish future service levels for the TEN-T road network.
- Identify technologies for climate change adaptation.
- Investigate processes for cost-effective adaptation.
- Establish field operational trials (FOTs) of integrated adaptation measures, in conjunction with other elements of FOR.
- Embed consideration of climate change in transport planning, design, operation and maintenance.
- The required R&D funding to achieve a European climate change resilient transport network will initially be relatively low, but will increase significantly once full scale FOTs are under construction.

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1. INTRODUCTION

1.1 FOREVER OPEN ROAD PROGRAMME

The Forum of European Highway Research Laboratories (FEHRL) initiated the Forever Open Road (FOR) Programme as the core of its fifth Strategic European Road Research Programme (SERRP V)[2] which ran from 2011 to 2016. Many of the areas identified in the FOR and FORx4 programme also feature prominently in FEHRL's update of SERRP running from 2017 to 2020[3]. The FOR Programme works towards developing a next generation of advanced and affordable roads that can be adopted both for maintaining the existing network and building new roads. This will enable future road operators to adopt emerging innovation, whilst overcoming the increasing constraints on capacity, sustainability, reliability and integration. The overall aim is to facilitate meeting societal needs in terms of mobility and accessibility for the 21st century.

The next generation of roads will require high levels of adaptation, automation and resilience. These three elements will define the next generation of road as follows:

- **The Adaptable Road:** focusing on ways to allow road operators to respond in a flexible manner to changes in the road users demands and constraints.
- **The Automated Road:** focusing on the full integration of intelligent communication technology applications between the user, the vehicle, traffic management services and the road operations.
- **The Resilient Road:** focusing on ensuring service levels are maintained under extreme weather conditions.

This document presents an update of the Resilient Roadmap to reflect on progress against Milestones and to reflect on any changes to innovation concepts based on current knowledge. The document describes the Resilient Road Element of the FOR Programme and has been developed through a series of workshops and technical input from experts and practitioners from FEHRL and supporting organisations. Annex 1 details the participants and their roles in developing this document.

1.2 THE RESILIENT ROAD ELEMENT

This Roadmap aims to determine how road transport infrastructure can be adapted to reduce the adverse impacts of projected climatic changes. The Roadmap is concerned only with adapting the infrastructure (increasing the resilience) to the potential effects of climate, not with the mitigation of climate change (efforts to reduce carbon emissions). Mitigation efforts will be facilitated by the Adaptable Road Element of FOR.

The Resilient Road Element is aimed at ensuring that the road network remains open under extreme weather conditions. Within this element, innovation themes will address the adaptation of road operations and management of the effects of extreme weather (flooding, snow, ice, storm, drought, heat) to such an extent that adequate service levels are ensured. Innovation technology will be key to the development of resilient solutions that can overcome the challenge of ensuring availability of mobility; these include improved materials, soil strengthening and rock stabilisation, improved water management, early warning systems based on local weather forecasts and dedicated weather proofing systems. This needs to be supported by appropriate changes in behaviour and inclusion of climate change risk in decision-making.

An additional area of interest not covered in the original roadmap is that of increasing resilience to man-made (e.g. accidents, vandalism or terrorism) as well as natural hazards. This has been recognised as an issue in a number of EC Horizon 2020 calls and is also highlighted in FEHRL's SERRP programme for 2017 to 2020.

1.3 SOCIETAL CHALLENGES

The FOR Programme will contribute substantially to the way the road transport sector addresses societal challenges[4]. Table 1 shows the Indicators and Guiding Objectives that FOR will help to address, specifically in meeting the challenges of decarbonisation, reliability, safety & security, liveability and affordability in terms of costs to society.

[2] Strategic European Road Research Programme (SERRP V), 2011 – 2016, FEHRL
[3] Strategic European Road and cross-modal Research and implementation Plan, 2017 – 2020, FEHRL
[4] ERTRAC Strategic Research Agenda 2010: Towards a 50% more efficient road transport system by 2030

Societal challenge	Indicator	Guiding objective	Adaptable	Automated	Resilient
Governance	Customer satisfaction	≥95% customer satisfaction	●	○	○
	Whole life cost	20-30% improvement vs 2010 by 2030	●	○	
	SME spend	33% spend with SMEs	●		
	Green procurement	≥ 50% green procurement in EU	○		●
Cross and multi-modal integration	Road network as part of integrated transport system	Target 100% capacity use	●	●	●
		+30% freight transport efficiency	●	●	●
	Infrastructure response to future mobility scenarios	+30% improvement and increase of infrastructure utility	●	●	●
	Air quality	Policy compliance	●		●
Maintenance & upgrading	Upgrading	-50% time lost to upgrades	●	○	
	Life extension	+50% extension of infrastructure life	●	○	
	Self-explaining and forgiving road	+40% reduction in KSIs	●	○	
Digitalisation	Adaption to automated vehicles.	+20% increase in capacity for mobility	●	●	
	Infrastructure investment	20-30 cost savings vs 2010 baseline by 2030	○	●	
	Big Data, BIM, IoT	30% cost savings in design /construction by 2025	○	●	
	Traffic management	30% reduction of congestion	○	●	○
Carbon & Environment	Embedded CO_2 reduction	-30% intensity to construct, operate & repair	●		○
	Decarbonisation/electrification	-40% CO_2 emissions and air pollutants	●	●	○
	Energy harvesting	Net energy production	●		
	Reduction in rolling resistance	Lowest practical achievable	●		
	Reuse & recycling	100% concrete recycling	●		
Resilience	Adaptation to extreme weather, climate change & man-made hazards	+50% reduction in downtime +10% improvement in service levels	●	○	●
Safety & Security	Improved safety in extreme weather conditions	+40% improvement	●	○	●
	Safety improvement due to digital environment	+40% reduction in KSIs (by 2030)	●	●	○
	Safety for road operatives	No road workers on foot on live carriageway	●	●	
	Safety for vulnerable road users	KSIs in view of proposed rise in active travel	●		

● **strong link** ○ **moderate link**

Table 1: Societal challenges addressed in the FOR Programme (source: SERRP Programme 2017 - 2020)

The Resilient Road contributes to all of these objectives by increasing the resilience of the road network to the effects of climate change and extreme weather events as outlined in the text below.

Decarbonisation > The Resilient Road is expected to help decarbonisation by reducing traffic delays and the need for the lengthy re-routing of traffic. In addition, the design and construction of low embodied energy infrastructure elements that are suitable for the climatic conditions in which they are situated will help decarbonisation and improve resilience. This, in turn, promotes resource efficiency and the reduction in maintenance activities.

Reliability > Adaptation of the road network to extreme weather events will increase the reliability and availability of the road network by keeping it open during extreme weather events.

Safety and Security > The Resilient Road has a key role to play in ensuring safety, in that whilst improving the reliability and availability of the network, it will ensure adequate safety and security levels by reducing the impacts and effects of adverse weather conditions. Examples of this include improved drainage and pavement materials avoiding pooling of surface water in heavy rainfall and maintaining skid resistance, preventing snow and ice through automatic de-icing systems, and improved resilience of pavements to extreme temperatures (both hot and cold). Ensuring reliable operation in all weather conditions will help improve freight security.

In addition, proper consideration needs to be given to man-made events, as well as weather and climate hazards. The Resilient Road can help to address some of these, whilst the Automated Road will consider areas such as cyber-security and the Adaptable Road will consider self-explaining and forgiving roads.

Liveability > Strong interactions between the Resilient and Adaptable Road Elements will ensure the design of a road with low noise, low emissions and protection of the natural habitat. Many of the elements related to ensuring operation in extreme weather, such as porous asphalt, will also aid in noise reduction, whilst prevention of flooding and a holistic overview of transport and land planning will minimise the impact of the road on the natural habitat in which it sits.

Cost reductions > It is important to consider the economic benefits of improving the ability of the road network to better withstand the effects of climatic events, and prioritising which construction and maintenance practices are required, in the most cost effective manner.

Cost reductions will arise from:

- Increased network availability and reduced delays to traffic.
- Lower time lost to maintenance and repair activities.
- Longer lasting infrastructure elements that are appropriate to their climatic conditions, giving an overall lower whole life cost.
- Consideration of the life-cycle cost implications of extreme weather events, and the funding levels required to enable the desirable levels of service to be achieved.

2. EXTERNAL DRIVERS FOR THE RESILIENT ROAD

2.1 CHANGING CLIMATIC CONDITIONS

Safer, more secure and efficient transport systems are essential to the functioning of business and society; the disruption caused by extreme weather events such as snow, flooding, storm events (wind) or heat are evident and have implications for all travel modes. The economic costs of current extreme weather events are significant, even for relatively limited losses of availability. It is reported that extreme weather conditions cost the EU's transport system at least €15 billion annually[5], although the WEATHER project estimated around €2.5 billion[6]. In addition to the cost of repairing damage caused to the transport infrastructure by extreme weather events, there are the wider external costs to society, such as delayed delivery of goods, people unable to get into work and reduced custom for local businesses. These are often manifested in a cost-benefit analysis as increased vehicle operating costs, increased travel time, and increased accident costs.

Climate change can manifest itself by gradual changes in climate parameters which, unlike extreme weather events, can go unnoticed yet still have an effect on the durability and functioning of road infrastructure; examples include steady increases in temperature and ultraviolet (UV) exposure, a rise in sea level and changes in groundwater levels. There is definitely a requirement for countries to review their design standards and maintenance regimes accordingly and adapt them to the changing climatic conditions. The use of downscaled regional climate projections can thereby help to differentiate guidelines locally and thus stipulate adaptation measures only where necessary. It is likely, however, that the main effects will not be related to, for example, a mean increase in temperature of 2° centigrade or an increase in annual precipitation of 10%, but rather an increase in the number of days per year that the temperature exceeds a threshold that can cause damage to asphalt, or an increased occurrence of extreme rainfall events.

It should also be recognised that some effects might be positive for some regions given the different impact distribution, for example lower winter maintenance requirements in some areas and reduced winter damage. Conversely, in some northern or mountainous areas, there could be increased freeze-thaw cycles with warmer winters. It should also be noted that weather can vary considerably around average variables, and even with warmer winters there is still the potential of a severe winter such as that experienced in much of Europe during 2010/2011. For road owners and operators, it is important to understand the potential future climate in order to respond accordingly.

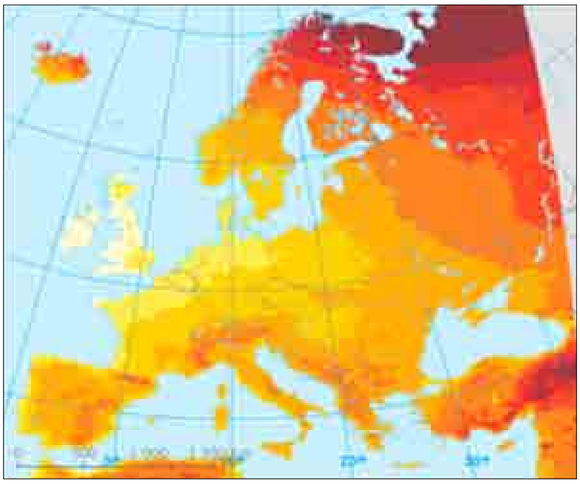
Some uncertainty exists about the potential impacts that climate change may cause, not least because of uncertainty as to the international response in reducing greenhouse gas (GHG) emissions (mitigation). There is also some uncertainty in areas where further research is required to better understand the potential impacts and spatial and temporal gaps in the data used for modelling weather. The purpose of this Roadmap is not to go into the scientific details of climate change, but to examine what potential impacts there might be on the transport infrastructure and what adaptation measures could be employed to reduce the adverse impacts. The predicted impacts and resulting vulnerabilities are considered below.

2.2 CLIMATE CHANGE PROJECTIONS

Projected temperature and rainfall patterns across Europe are presented below, showing a general increase in temperature across Europe, but particularly in the far south Mediterranean areas, in eastern and the far north of Europe and in mountainous regions. In terms of precipitation, generally only the Iberian Peninsula, southern Italy, Greece and Turkey are projected to have an overall decrease in annual precipitation. What is striking is that whilst most areas of Europe are projected to have an overall increase in annual precipitation, only Scandinavia and the far north

[5] EWENT, http://www.vtt.fi/inf/pdf/technology/2012/T36.pdf
[6] OECD/ITF (2016) Adapting Transport to Climate Change and Extreme Weather. Implications for Infrastructure Owners and Network Managers.

east of Europe are projected to have a corresponding increase in summer precipitation, the remainder of Europe shows either little change or in many a projected significant decrease in summer precipitation. It is clear, therefore, that these areas are projected to have a significant increase in winter precipitation.



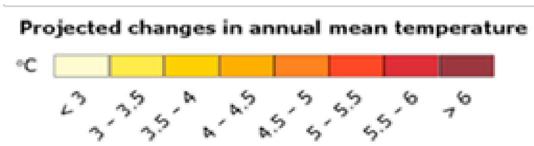
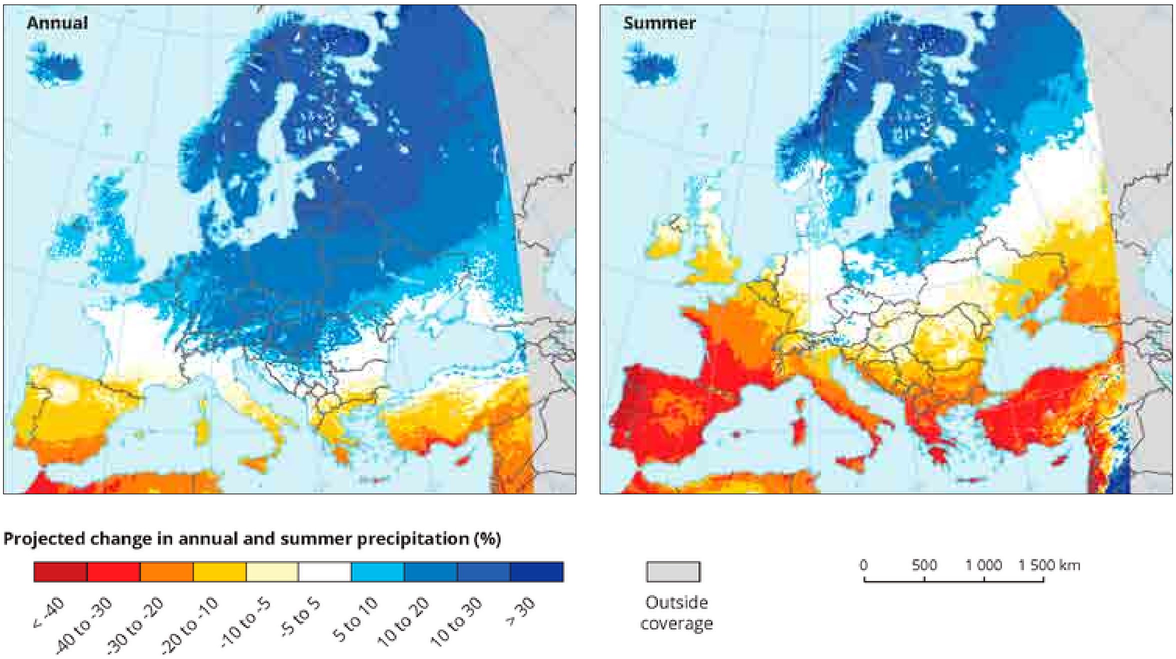


Figure 1: Projected Changes in annual temperature and annual and summer precipitation for the period 2071 to 2100 compared to 1971 to 2000[7]



As the climate changes, extreme weather events may become more frequent, intense and longer lasting. Vulnerability to climate change varies widely across regions:

- In low lying countries with islands and extensive coastlines such as Denmark[8]; sea level rise has affected land drainage, causing groundwater to reach the surface temporarily or permanently, causing 'blue spots' triggering road closures.
- The European Environment Agency[9] predicts that "Sea level rise will continue for many centuries, even if GHG emissions and temperature are stabilised. The main uncertainty for multi-century sea level rise is how fast the large ice sheets will disintegrate. Individual studies have suggested that the melting of the Antarctic ice sheet could contribute up to 15 m to sea level rise by 2500 under a high emissions scenario, but these projections are associated with very large uncertainties".

[7] European Environment Agency 2014
[8] Kristiansen, J R: 2010. Rising groundwater levels can cause permanent flooding of roads. Transport Research Arena Europe. Brussels.
[9] EEA (2017). Climate change, impact and vulnerability in Europe 2016. An indicator-based report.

- The Mediterranean area is becoming drier, making it more vulnerable to drought and wildfires, whilst northern Europe is getting significantly wetter, and winter floods could become common.
- Europe's far south, east and the Arctic show significantly increased temperatures, as do the Alps. In addition to changes in general precipitation, there could be changes to the proportion falling as snow or rain, changes in the melting of snow and ice, and in the freeze-thaw patterns.

2.3 POTENTIAL IMPACTS OF CHANGING CLIMATE ON TRANSPORT INFRASTRUCTURE

Extreme weather events and man-made acts will impact on both the infrastructure and network operations, and can be both short term (e.g. surface flooding blocking a road or high winds temporarily closing a bridge) or longer term (e.g. significant damage to infrastructure such as a bridge collapsing as a result of scour or high river flow). Whilst there will be various changes across the geographic areas of Europe, some of the risks to the TEN-T Road Core Network including connections with secondary and tertiary road networks are outlined below:

- Flooding either through precipitation or potentially rapid snow/ice melt, groundwater and sea level rise in some regions and some of the associated effects such as:
  - Operational disruption, reduced network availability and blockages.
  - Bridge scour, inundation of tunnels and landslides.
  - Overloading of drainage systems.
  - Saturation of the unbound layers, resulting in loss of fine material, settlement and failure.
  - Saturation of the subgrade causing a reduction in strength.
- Hotter, drier summers leading to a reduction in sub-surface water, causing shrinkage of the sub-surface and inducing cracking. Increasing changes in sub-surface water can cause soil to shrink and expand significantly, causing the overlying pavement layers to heave and subside.
- In periods of hot weather, asphalt surface layers can become susceptible to rutting and deformation. In addition, high temperatures can make newly laid asphalt remain workable for an extended time, making it difficult to maintain profile during compaction.
- Thermal gradients can create uneven internal stresses, giving rise to curling or warping in concrete pavements, damage to bridge expansion joints and to steel bridge decks if the asphalt has been removed for maintenance.
- Reduction in vegetation due to higher temperatures and drought, and/or higher wind speeds could increase erosion processes on embankments, leading to them becoming unstable.
- Intense rainfall events causing erosion or landslips/landslides on embankments. Extreme rainfall events in areas with reduced vegetation, described above, would intensify erosion, whilst generally wet weather increases the occurrence of potholes in asphalt roads.
- A milder climate could have implications for northern areas of Europe where the ground is currently frozen during winter, through increases in the freeze-thaw process.
- Conversely, winter maintenance requirements may decrease in many areas due to a milder climate, whilst changes in springtime snow melt and the proportion of precipitation falling as rain or snow might result in less flooding. Because of higher temperatures in the winter, some regions face problems related with an increased number of annual frost-thaw cycles (temperature fluctuation around zero), which cause damaging effects to road infrastructure resulting in decreased lifetime.

2.4 VULNERABILITY ASSESSMENT

In considering strategies to deal with the impacts of climate change on transport infrastructure, it is likely that a staged approach will be implemented based on assessment of vulnerability, followed by the development and implementation of adaptation strategies. There are key road, rail, inland waterways, ports and airports across European Member States whose continued efficient function is vital to maintain European economic competitiveness, as well as social connectivity, and there is a significant level of interconnectivity between modes. These transnational assets are likely to take priority, followed by national, regional and local transport networks.

The Intergovernmental Panel on Climate Change define vulnerability (to climate change) as an integrated measure of three dimensions: exposure, sensitivity and adaptive capacity (the social and economic means to withstand climate change impacts). Exposure and sensitivity will determine the set of potential impacts.

This Roadmap concentrates initially on the TEN-T network, based on the costs and benefits of maintaining the connectivity of key links; however, the technical principles of increasing resilience can be applied to all transport networks, and might be particularly relevant for urban networks, not least given the importance of maintaining connectivity across modes in cities. The TEN-T network represents the key transnational road, rail and inland waterway/ports assets and their protection against the possible effects of climate change is imperative; this document focuses on the road sector, recognising its dominance within the overall transport network.

In considering resilience, the interdependency of other infrastructure elements, telecommunications and power is vital in maintaining a functioning transportation network, e.g. power and telecommunications are vital in ensuring that transport networks function efficiently, particularly public transport; equally, workers need to be able to access power plants and control centres to keep them operational.

A further factor to consider is the vulnerability of specific routes, for example the severance of a major road or rail link with little other suitable rerouting options could leave a region cut off, for example when the only rail route to the south-west of England was destroyed during the storms of 2014, it was imperative the motorways remained operational.

Figure 2: Key railway line linking the south-west of England destroyed in storm in February 2014 (Picture Courtesy of Network Rail)

In addition to vulnerability from natural hazards, infrastructure owners and operators need to ensure resilience against man-made hazards, whether through vandalism or a malicious act. It should be possible to expand the vulnerability criteria to include man-made hazards, in particular for critical assets such as bridges, structures and tunnels.

2.5 AGEING INFRASTRUCTURE

The development of road infrastructure throughout Europe varies greatly. A REFINET project report[10] states that the sector of the construction and renovation of infrastructures today represents around $4,000 billion worldwide, which is anticipated to double by 2025. It reports that Europe has one of the densest and most developed infrastructure networks in the world, with most construction between 1960 and 1970, with a design life of 50 years. Extreme weather events and the long-term effects of climate change, together with increasing traffic loads will put further strain on Europe's infrastructure. Maintaining this infrastructure and protecting it against climate and traffic conditions not envisaged at the design stage is of great importance, and cost-effective solutions to extend the service life are required. Conversely, some regions are still developing their road infrastructure networks, and cost-effective solutions to design and construct new roads with in-built resilience are thus desirable.

In a report to the UK Government[11] following major storms over the 2013-2014 winter, one recommendation was that simple maintenance activities such as routine inspection and maintenance of drainage systems, clearance of vegetation and at-risk trees and monitoring of structures and embankments were important tasks that have not always been given the priority they should have, and that budgets in these areas were often constrained, as opposed to capital spending. In addition, the report noted that spending on resilience is largely event-led and reactive. This was also evident in the US, where a key learning following Hurricane Katrina in Louisiana was to maintain the existing infrastructure regularly, rather than necessarily building more[12].

2.6 TRANSPORT SERVICE LEVELS

In recognising that climate change will have different impacts in different regions of Europe, and that there is a critical network of transport modes that require protection, an obvious starting point would seem to be to determine the key infrastructure assets that might be at significant risk and agree service levels for various tiers of infrastructure.

For example, for the Tier 1, TEN-T networks that are key European transport corridors, it might be required that they operate at 99.99% availability, whereas local roads might be assigned a lower availability level based on the cost-benefit of keeping them operational. The point at which the service levels are set will have a significant bearing on the required adaptation measures.

There are also key interchanges or routes that require a high level of resilience, for example those that carry other utilities and services or where a number of key roads interlink. It is important to develop inventories of infrastructure assets and assess aspects such as the importance of the assets in terms of kilometres travelled, freight tonnage, evacuation routes and community priorities.

As the dominant sector in terms of passenger and freight movements across Europe, the road sector offers the greatest flexibility in terms of re-routing opportunities and connection to other modes. In order to determine the Roadmap and the milestones, the first step is to determine what is envisaged by a climate resilient road; i.e. once a target is defined, the steps to achieve that target can be identified.

It will not be possible to make a road or transport system totally resilient to climatic events, and certainly not at an acceptable economic cost.

In working towards a 2025 timeline, the following specific targets are considered appropriate:

- The focus of this Roadmap is for the resilience of the core network (TEN-T), however the principles can be applied to all roads.
- Service levels should be set, specifically with a target for a reduction in downtime of 50%; across the TEN-T network and major routes; this will cover all aspects of downtime, and not just that related to weather events.
- There is a target of at least three corridors that will be made resilient, with downtime reduced by 50% in accordance with the targets presented in FEHRL's SERRP V and subsequent SERRP 2017-2020 document, although it is noted that the 'Research for Future Infrastructures in Europe (reFINE)' target is 100% reliable urban infrastructure in extreme events.
- Newly built roads and roads that are undergoing reconstruction will be designed to be resilient to the future predicted climate and vulnerabilities should be accounted for and/or avoided. This requires 'Intelligent Road Design' and the revision of the relevant guidelines.
- There is a challenge in competence and skills shortage currently which should be addressed.
- Maintenance and management costs and long term (life-cycle) effects should be accounted for.

[10] Zarli, A; Bardeu, L; Segarra, M (2016) REFINET Rethinking Future Infrastructure Networks, Transportation Research Procedia, pp 448-456.
[11] 2014. Transport Resilience Review - A review of the resilience of the transport network to extreme weather events. ISBN 9781474106610.
[12] FEHRL USA Scanning Tour 2012. Climate Adaptation for Roads.

In 2025, a climate resilient transport network will ensure that key routes are available at appropriate safety and security levels to the user in all weather and climate conditions. Effectively this means the network service might be limited for an acceptable period of time, but that routes that are key to the European economy and society would not be blocked. The selection of key road routes will be subject to a cost-benefit evaluation over the corridors/routes involved, which will consider not only the level of resilience achieved per spend, but factors such as the importance of the route for freight, connectivity between major conurbations and the availability (or lack) of alternative routes.

2.7 PREPARATION FOR THE USE OF E-MOBILITY, INTELLIGENT DRIVING SYSTEMS

Advances in electric and autonomous vehicles and requirements for decarbonisation in the road sector have pushed forward the development of e-mobility and intelligent driving systems. This will require central data servers to coordinate all information and activities. This is of relevance to the Resilient Road in so far as increased control and monitoring through, for example, sensor systems and intelligent driving systems, will allow road operators to implement traffic control measures in response to weather events to provide routing information, and will also enable vehicles to act as sensors and provide information on road and environmental conditions. Future autonomous mobility scenarios could help improve resilience by increasing safety, through avoiding sharp braking and maintaining safe following distances.

2.8 LAND USE PLANNING

More widely, there is an opportunity to integrate transport and land use planning more effectively, so that roads are considered to be part of the overall environment in terms of water management and biodiversity. There have also been examples of integrating counter-terrorism measures such as steps and barriers for hostile vehicle mitigation into the urban realm, whilst providing an aesthetically pleasing environment.

In the future, the road network could interact more harmoniously with its environment, for example by acting as a reservoir or flood barrier depending on location. As such, links between transport planning and land use planning will be vital, and research programmes are required with land-use and resilience to extreme weather in mind.

With potential scenarios such as platooning and autonomous vehicles and mobility as a service replacing private vehicle ownership, the future transport infrastructure requirements could change significantly, as could their integration within the environment. Fully autonomous vehicles will occupy a far smaller area of road space due to closer running and more accurate lane keeping, and as such will open up additional capacity on certain routes, to the extent that in some areas there could be more infrastructure than required. This offers opportunities for the remainder to be repurposed for other means, such as improving drainage capacity or proving opportunities for other modal transport.

2.9 SAFETY AND SECURITY

There have been many studies on the influence of weather conditions to road safety and accident frequency. A SWOV factsheet[13] lists the following factors and impacts:

- Precipitation and fog increase the risk of accidents. Drivers tend to adjust their driving to take account of the conditions, but not to the degree required.
- Wind can cause disruption, particularly for high-sided vehicles. They may even tip over on bridges.
- Ice can form quickly, causing an unexpected skid hazard for drivers. This is exacerbated by differences between surfaces, for example ice can form more quickly on porous asphalt and it might also be more difficult to de-ice effectively. Better winter road maintenance for bridges and usage of innovative solutions such as temperature controlled pavements or environmentally-friendly and effective materials/chemicals could improve safety here.
- High temperatures can affect driver concentration, increase aggression and also cause tiredness and also affect asphalt pavements, causing safety hazards, e.g. rutting.

The incidences of extreme weather are forecast to increase, and so solutions in design and construction, maintenance, operation and management are required to maintain and improve the levels of safety whilst increasing the resilience of the infrastructure.

[13] SWOV, Institute for Road Safety Research, The Influence of Weather on Road Safety, February 2012

3. SCOPE AND APPROACH

Climate change will have an impact on all aspects of road transport. Currently, the transport network struggles with extreme weather events both in terms of operational disruption and damage to the road infrastructure. Facing this situation, road authorities need to be supported with appropriate strategies to ensure the reliability, availability, maintainability and safety of road infrastructure.

This Roadmap aims to support road authorities by providing a research agenda that should enable a better understanding of climate risks and vulnerabilities, adaptation options and management strategies. The innovation themes and associated research requirements are designed to support the overarching milestones initially set for 2015, 2020 and 2025-2030. With the 2015 milestone now reached, this document will focus on reviewing progress and revising the remaining milestones and research themes based on current understanding.

3.1 INNOVATION THEMES

This section presents a programme of research based on three innovation themes, and specific topics considered vital to facilitate transitions towards the Resilient Road, with a suggested approach and indicative milestones planning for each topic. These milestones will not be representative for all European countries, as some Member States will be 'early adopters', whilst others will follow a timeline which suits their particular socio-economic situation.

There is a balance to be made in ensuring that the future road transport system is accessible, satisfies requirements for sustainable economic growth, and yet is resilient to climatic impacts. This requires a holistic approach covering the development and implementation of technologies and methodologies and management and adaptation strategies, as well as revised technical specifications. The research and innovation activities focus on a broad range of themes. The key themes are described below, with specific research and innovation topics presented in section 3.2.

Development and implementation of risk-based methodologies

1. Development of risk-based methodologies to assess the vulnerability of the road network to extreme weather events, longer-term impacts of climate change and shifts in climatic zones;
2. From the results of the vulnerability assessment, production of maps showing potentially vulnerable elements of the TEN-T road network;
3. Estimation of economic costs of adaptation measures and development of risk-based procedures to consider the cost of disruption due to extreme weather versus the cost of adaptation.

Development and application of technologies

1. Design of resilient drainage systems, soil strengthening and rock stabilisation techniques and early warning systems;
2. Resilient asphalt and concrete pavements (mixture and pavement design, paving technologies) and methods of increasing skid resistance;
3. Long-life and low maintenance measures for increasing the resilience of existing bridges, including foundations, pre-emptive protection systems for tunnel structures against flooding and solutions for the conservation of groundwater reserve during tunnel construction and operation;
4. Rapid and automated inspection and survey methods, as well as sustainable maintenance measures and techniques for pavement, sub-surface, structures and drainage;
5. Automated and remote sensors for measuring environmental conditions and change;
6. Interaction between vehicle/infrastructure/driver;
7. Improved user information, especially to address the management of extreme weather events and infrastructure adaptation at regional level and across country borders (neighbouring countries).

Development and introduction of management and adaptation strategies

1. Development of guidelines for maintaining the expected performance levels of infrastructure systems and strategies to cope with disruption during extreme weather events;
2. Development of guidelines supporting seamless maintenance and pavement preservation with elements of pavement management system (PMS) approach;

3. Development and improvement of models to predict weather events and traffic congestion, and to assess the impact of real-time management systems to provide the early warning of extreme events and instigate intelligent re-routing and modal shift;
4. Development and implementation of adaptation strategies and guidelines to assist the implementation of newly built and adaption of existing infrastructure;
5. Integration of the above with emergency services systems;
6. Sensor and communication systems to provide real-time information for the road user and infrastructure manager.

3.2 RESEARCH AND INNOVATION TOPICS

Using these themes, the objectives and enablers for developing resilience in the performance and management of the TEN-T network have been established. The supporting research needs have then been identified with a view to the application of practical measures for each theme.

An important issue that came up in the course of the update of this roadmap is cooperation between the different transport modes. Not only do they rely on similar climatologic input data, but the risk assessment methodologies can either be applied directly to other modes (e.g. for landslide hazards) or adapted relatively easily. And finally, adaptation measures should be developed and deployed in cooperation with the other transport modes.

Development and implementation of risk-based methodologies

Objective

To understand the vulnerability of the TEN-T road network to the effects of climate change and understand the range of benefits and costs of adaptation options.

Enablers

- Climate projection models/climate impact models,
- Vulnerability toolkits,
- Cost-benefit analysis tools.

Application

There are a number of vulnerability toolkits available, with the RIMAROCC[14] method being used to assess sections of both the Dutch and German TEN-T networks. An additional tool is SWAMP[15], which, along with RIMAROCC, was developed as part of the 2008 ERA-NET Road Call 'Road Owners Getting to Grips with Climate Change'[16]. The 2012 ERA-NET Road Call 'Road Owners Adapting to Climate Change'[17] has funded projects in climate modelling and vulnerability assessment. Its project CliPDaR (Climate Projection Data Base for Roads)[18] has published a guideline on the use of climatologic data suitable for the analysis of roads, based on freely available data. The use of those guidelines is highly recommended as a prerequisite for a harmonised risk assessment in Europe. The second project, ROADAPT (Roads of today, adapted for tomorrow)[19], provided a comprehensive method for risk analysis, including a huge database of adaptation measures. The RIVA method, developed for FEHRL German member BASt, is also a functional risk assessment tool that already yielded results on 10% of the German road network. The most recent CEDR Call recognised that a number of tools have been developed for road owners and that more work was required for them to be more widely implemented. In the Netherlands, the ROADAPT methodology has been tested and compared with the above-mentioned FHWA methodology in the InnovA58[20] project. Results will be reported in 2017.

Furthermore, the CEDR 2015 climate change Call 'From desk to road'[21] also focuses on implementation and applicability. The projects under this Call have started in 2016, or will start in 2017, amongst others the DeTECToR[22]

[14] http://www.cedr.eu/rimarocc-project-results/
[15] http://www.cedr.eu/swamp-project-results/
[16] http://www.cedr.eu/call-2008-climate-change/
[17] http://www.cedr.eu/strategic-plan-tasks/research/cedr-call-2012/call-2012-climate-change-road-owners-adapting-climate-change/
[18] http://www.cedr.eu/strategic-plan-tasks/research/cedr-call-2012/call-2012-climate-change-road-owners-adapting-climate-change/clipdar-project-results/
[19] http://www.cedr.eu/strategic-plan-tasks/research/cedr-call-2012/call-2012-climate-change-road-owners-adapting-climate-change/roadapt-project-results/
[20] https://www.innova58.nl/default.aspx
[21] http://www.cedr.eu/call-2015-climate-change-desk-road/

project (Decision-support Tools for Embedding Climate change Thinking on Roads). This project is producing tools and guidance aimed at putting into practice the latest research and embedding climate change adaptation in operations and procurement.

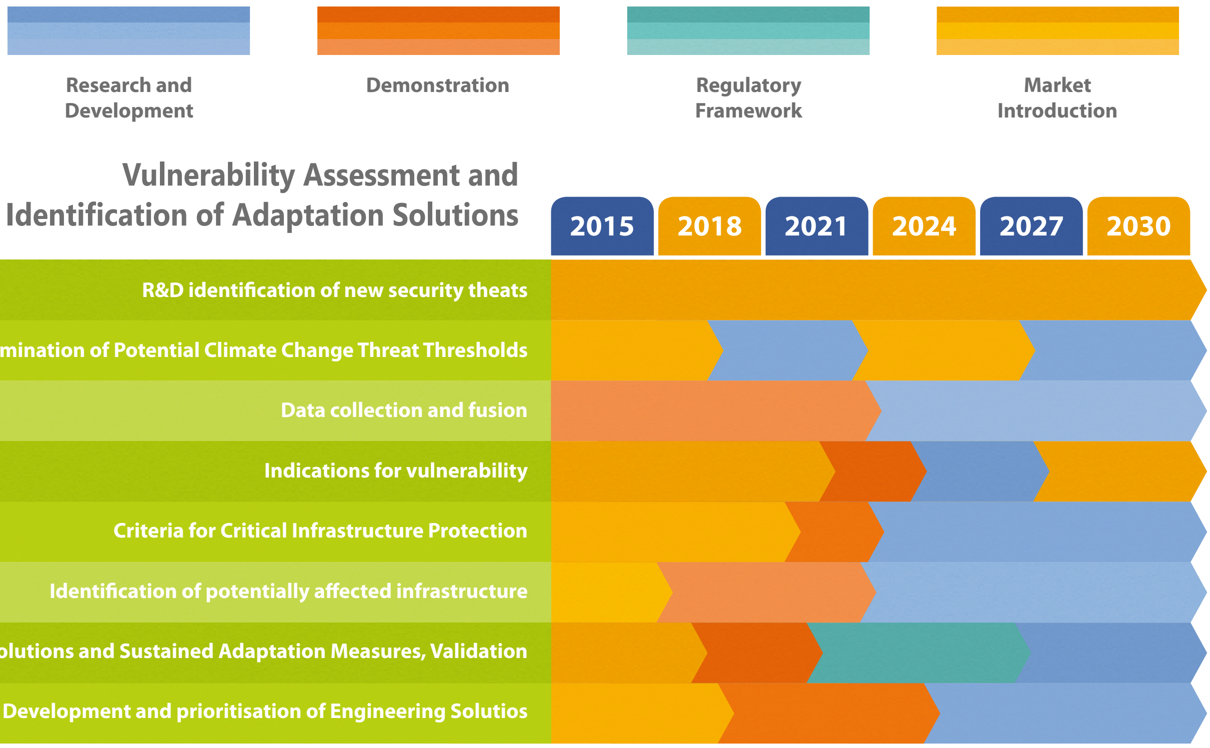
Regional climate projections are now available for Europe and can be obtained from the ENSEMBLES[23] and EURO CORDEX[24] websites. Similarly, gridded observational data are also available for Europe (e-obs) and can be used to make estimates of the current vulnerability to weather hazards[25, 26].

In the USA FEMA (Federal Emergency Management Agency) is using the quite advanced Hazus[27] programme, which is oriented for efficient mitigation, planning, response and recovery efforts caused by natural hazards. The US Federal Highway Administration (FHWA) has also developed a five-stage vulnerability assessment process.

Research needs

There is an on-going requirement for improved climate models, particularly in terms of downscaling from current predictions, and precipitation models; work is on-going on this topic in many meteorological centres worldwide, with communication and collaboration between climate scientists and road professionals key to understanding risk and acting accordingly. Such cooperation will address areas of interest to road operators, such as the extent to which downscaling is necessary.

The harmonisation of existing climate projections is important as it will generate the resulting input data for vulnerability assessments suitable for national road authorities. This could enable a more precise definition of the impact of extreme weather events on infrastructure, e.g. the development of threshold values for rainfall, which could trigger a requirement for the adoption of adaptation measures or revised maintenance requirements. Further improvements and common acceptance on risk models are also required. There is a requirement for economic modelling on the potential future disruption caused by climate change, and the cost-benefit analysis of adaptation technologies, including common systems.



[22] http://detector.trl.co.uk/
[23] http://ensembles-eu.metoffice.com/
[24] http://www.euro-cordex.net/
[25] Written communication from UK Met Office
[26] Climate-ADAPT Platform: http://climate-adapt.eea.europa.eu/knowledge/tools/urban-adaptation/introduction
[27] https://www.fema.gov/hazus-detail

Development and application of technologies

Objective

The objective is to develop and deploy cost-effective adaptation measures in order to increase the resilience of the TEN-T road network, whilst maintaining appropriate safety levels.

Enablers

- Existing adaptation measures/technologies
- Existing adaptation plans by, for example sector, city, region, nation
- Ongoing research into new adaptation measures
- Cost-benefit analysis of alternative measures and cost-effectiveness

Application

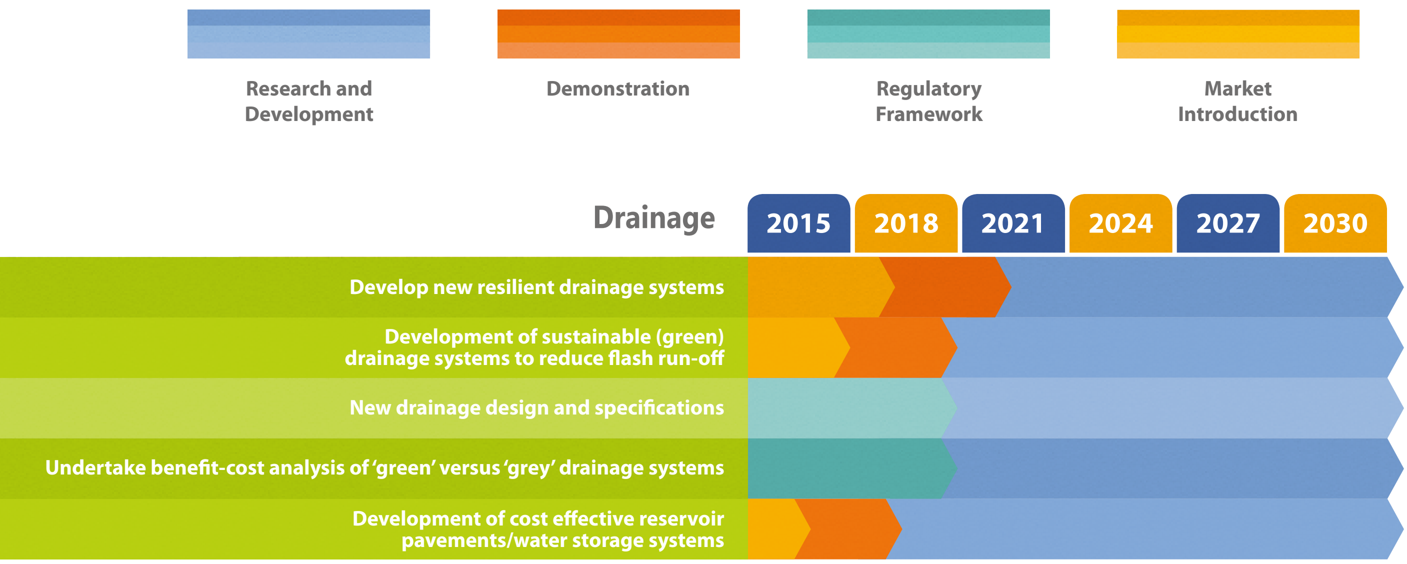
Different weather events will pose correspondingly different stresses to the various road elements; for example extreme heat may increase the propensity for rutting on asphalt pavements, whereas an extreme rainfall event might affect the sub-base or embankment. The majority of the elements on the network are interlinked and interdependent to a greater or lesser extent, and as such consideration needs to be given to individual elements, e.g. wearing course, sub-base, sub-grade, embankments, drainage, structures, foundations and tunnels and their influence on the system as a whole.

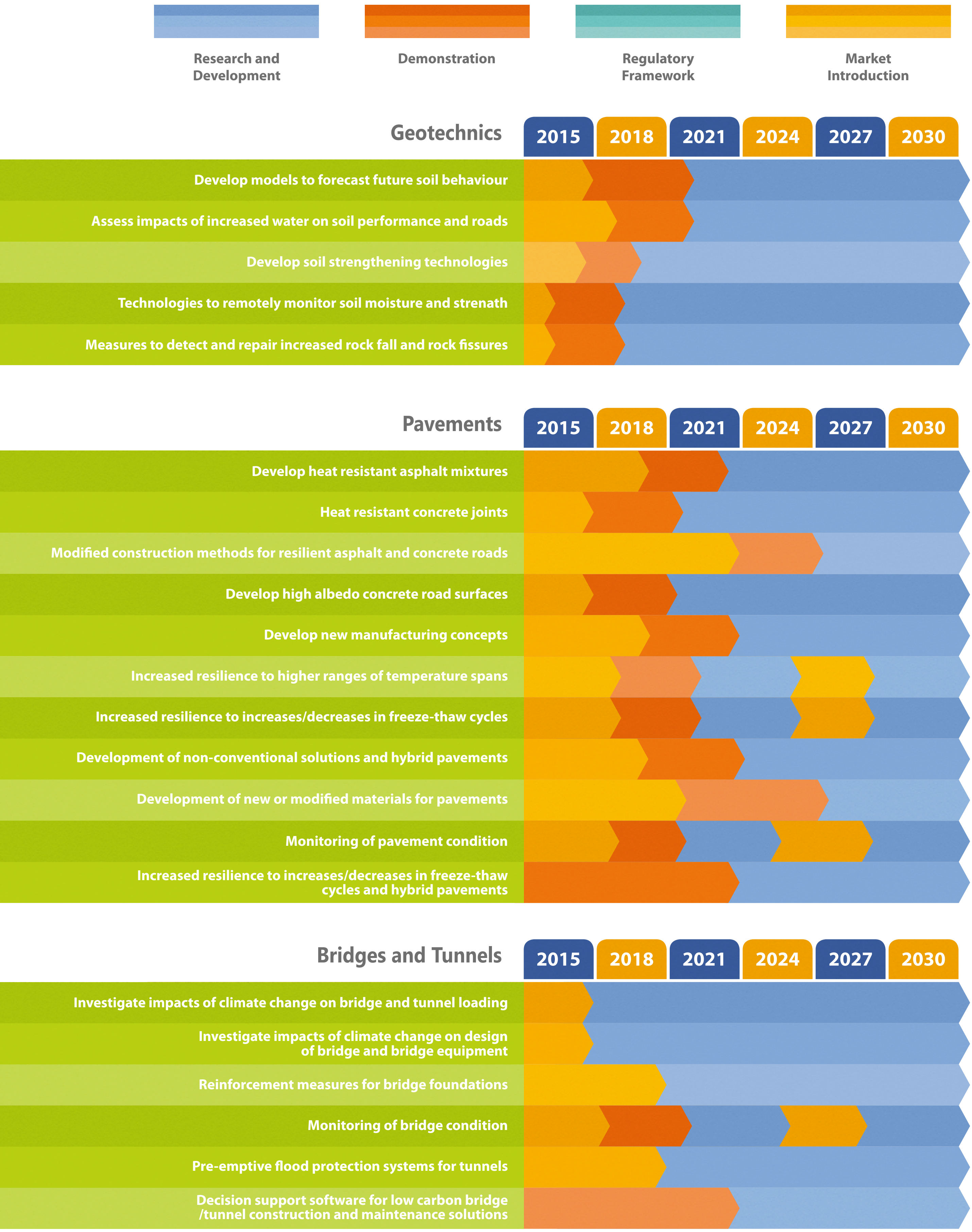
Research needs

There is a need to improve both concrete and asphalt pavements to protect them from the effects of extreme weather, although better drainage in the pavement surface and substructure is a more pressing need. Improvements in the drainage and resistance of the pavement sub-surface and embankments to fluctuations in extremes of water are required in order to prevent cracking through desiccation and strength loss or landslides through excess water. Additionally, bridges and structures, including foundations, require increased resilience to flooding and scour.

For northern and possibly mountainous regions, there is a requirement to increase the resilience of the pavement to freeze-thaw actions.

There will be an interaction with the Adaptable Road Element in so far as technologies developed here will be implemented by the Adaptable Road, and research themes in the Adaptable Road such as self-healing and self-cleaning will increase the resilience of the road in general. The following research topics are divided into geotechnics, road pavements and bridges and structures, although the interaction between these components is acknowledged.




Research and Development
Demonstration
Regulatory Framework
Market Introduction
Geotechnics
2015
2018
2021
2024
2027
2030
Develop models to forecast future soil behaviour
Assess impacts of increased water on soil performance and roads
Develop soil strengthening technologies
Technologies to remotely monitor soil moisture and strenath
Measures to detect and repair increased rock fall and rock fissures
Pavements
2015
2018
2021
2024
2027
2030
Develop heat resistant asphalt mixtures
Heat resistant concrete joints
Modified construction methods for resilient asphalt and concrete roads
Develop high albedo concrete road surfaces
Develop new manufacturing concepts
Increased resilience to higher ranges of temperature spans
Increased resilience to increases/decreases in freeze-thaw cycles
Development of non-conventional solutions and hybrid pavements
Development of new or modified materials for pavements
Monitoring of pavement condition
Increased resilience to increases/decreases in freeze-thaw cycles and hybrid pavements
Bridges and Tunnels
2015
2018
2021
2024
2027
2030
Investigate impacts of climate change on bridge and tunnel loading
Investigate impacts of climate change on design of bridge and bridge equipment
Reinforcement measures for bridge foundations
Monitoring of bridge condition
Pre-emptive flood protection systems for tunnels
Decision support software for low carbon bridge /tunnel construction and maintenance solutions

Development and introduction of management and adaptation strategies

Objective

The objective is to improve the strategic planning and general management and operational response of the road network to extreme weather events.

Enablers

- Existing asset management procedures
- Cooperative Intelligent Transport Systems (ITS) and communication systems
- Disaster management/emergency plans

Application

There are two separate but linked requirements regarding the strategic planning of the TEN-T network by the national road authorities. The first is to increase the resilience through understanding vulnerable sections and implementing adaptation mechanisms accordingly. The second requirement is the continued operation of the TEN-T network when challenging weather events are predicted or are occurring, in order to maintain as high a service level as possible. The ROADAPT (Roads of today, adapted for tomorrow, CEDR 2012 Climate call) provided a guideline and a database of adaptation strategies. This has been tested, for example, in the InnovA58 project in the Netherlands.

Research needs

The production of guidelines on the required performance levels for infrastructure elements is required to produce a baseline for climate change adaptation requirements.

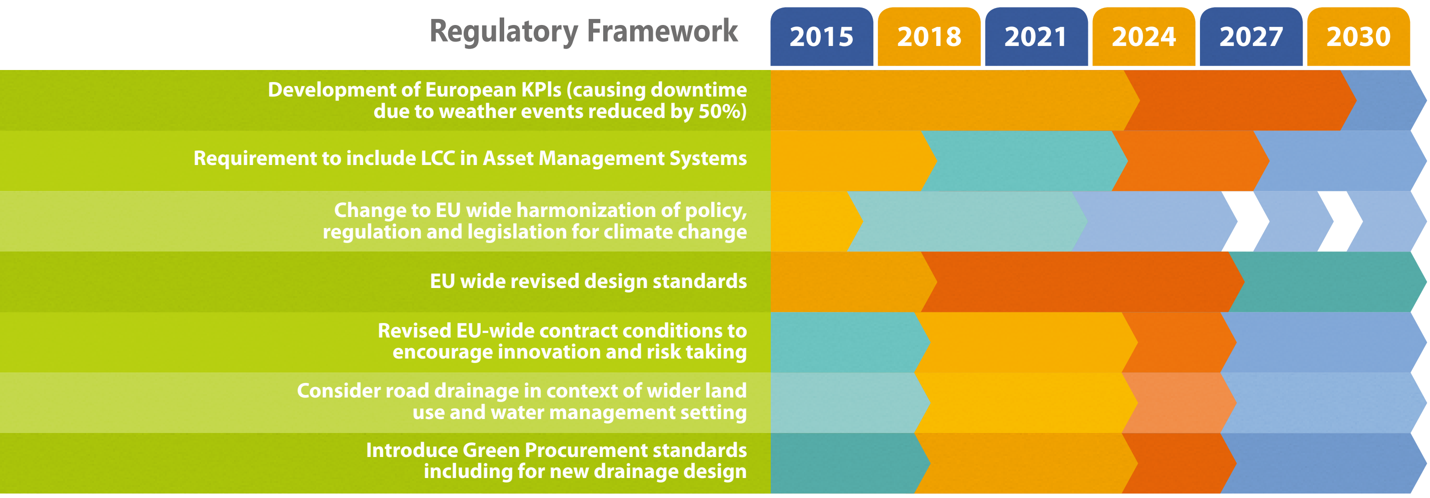
Improved weather prediction models to be used in conjunction with real-time weather and traffic information require development in order to provide early warning and trigger operational responses such as, for example, the restriction of access, changes to speed limits or re-routing. There is also a requirement for improved asset management, value management and maintenance strategies for the adaptation of infrastructure that will provide optimal cost effectiveness. An intermodal approach for adaptation measures should be considered.

There should be interaction with the Automated Road Element in terms of data gathering from various sensor systems and networks and translating that into reliable and real-time information for road users. This will include the use of ITS for traffic control for environmental purposes in varying traffic/weather conditions, e.g. to reduce speeds in extreme weather conditions. Also, real-time user information for drivers (e.g. through navigation or other in-car devices) of safe speed, safe distance on particular road sections during various weather conditions. Additionally, recommendations for eco-driving can be included, depending on the road geometry resulting in reduced negative impact on environment.

The research topics here come under Operational Management, with focus on the day-to-day management of transport infrastructure, and Regulatory Framework, which concentrate on the national or European strategic management of transport infrastructure.


Research and Development
Demonstration
Regulatory Framework
Market Introduction


Operational Management
2015
2018
2021
2024
2027
2030
New examination methods for stuctures
Investigate Effect of Climate Change on Highway Maintenance Costs
Impact of changing climatic conditions on flora and fauna
Adaption measures and economic impact
Risk based management procedures
Real time weather and traffic models
Real time drainage monitoring and maintenance measures to ensure drains are kept clear
Real time management systems to provide early warning of natural and man-made trigger events
Inteligent re-routing and modal shift strategies
International exchange of extreme event info (especially between neighbouring countries)
Asset Management tools for decision support
Post event recovery and management systems


Regulatory Framework
2015
2018
2021
2024
2027
2030
Development of European KPIs (causing downtime due to weather events reduced by 50%)
Requirement to include LCC in Asset Management Systems
Change to EU wide harmonization of policy, regulation and legislation for climate change
EU wide revised design standards
Revised EU-wide contract conditions to encourage innovation and risk taking
Consider road drainage in context of wider land use and water management setting
Introduce Green Procurement standards including for new drainage design

4. ROADMAPS AND MILESTONES

The Roadmap will provide solutions that are ready to be implemented by the national, regional and local infrastructure authorities. The envisaged build up was from single technology trials from around 2013 towards full systems proving on a network scale around 2020. From 2020, the Roadmap will be concerned with supporting and facilitating the roll-out activities by the authorities. It is in this stage that climate change resilient transport will be implemented at a network level.

Milestones were proposed for 2015, 2020 and 2025 for short, medium and longer-term implementation, respectively, and are outlined in Figure 3. It is recognised that research and development for different technologies would progress at different rates. This is indicated in Section 3. The Roadmap is intended to be an active document, and it is recognised that it covers a medium to long timescale; as such, it will be reviewed at regular intervals to recalibrate the targets and approach.

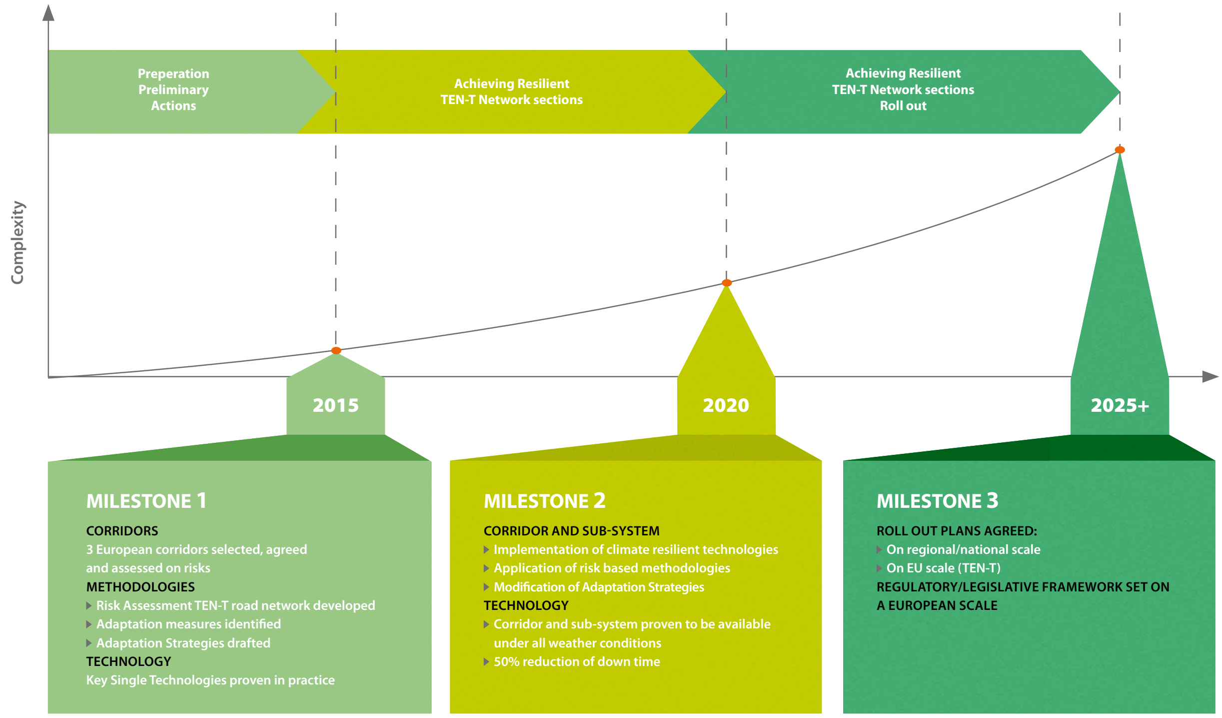


Figure 3: Outline Milestones for Climate Change Resilient Transport

4.1 MILESTONE 1: PREPARATION AND PRELIMINARY ACTIONS (2015)

The main topics of Milestone 1 are the selection of three TEN-T pilot corridors, the collection of background information and implementation of a unified database on transport-related climate change effects/scenarios and the application of single technologies on selected infrastructure elements. The table below indicates progress against the main Milestone 1 targets.

TARGET	PROGRESS
CORRIDOR SELECTION	
Selection of three TEN-T pilot corridors	Not formally selected, although the Dutch and German motorways have been selected for assessment with RIMAROCC. In addition, there has been a Rotterdam to Vienna corridor selected for smart motorways. The corridors have been selected and furthermore, there are sections where not only road but rail and waterways are part of the corridor as well, which gives the opportunity for an intermodal approach.
Preliminary assessment of weaknesses based on currently available methodologies (RIMAROCC, SWAMP, RIVA, ROADAPT and other available national tools).	A number of assessments in these areas have been undertaken on various sections of the TEN-T network.
Development and updating of design standards for the predicted future effects of climate change and extreme weather events.	The Netherlands, Germany and others have developed design standards for extreme weather but this work has only begun.
Encouragement of road authorities to carry out pilot projects for eliminating identified weaknesses.	As above on selected TEN-T corridors
METHODOLOGIES	
Review, analysis and assessment of existing regional climate predictions regarding European transport needs.	CEDR project CliPDaR has published guidelines for the common use of a harmonised data set of projection data.
Fusion of regional climate predictions with the aim of gaining a unified knowledge database specific for European transport (TEN-T).	See above
Further development and improvement of existing risk-based methodologies for assessing the vulnerabilities of transport infrastructure.	Numerous CEDR projects on this including several ongoing in the CEDR 2015 Climate Change Call 'From desk to road', which also focuses on implementation and applicability. Also work on vulnerability models undertaken in the USA RIVA has been developed and applied on 10% of the German federal road network, still it is not yet including all potential climate impacts. Integration of the missing impacts is ongoing work. ROADAPT also developed a comprehensive methodology that has been tested and compared with the FHWA methodology in the InnovA58 project.
Identification of adaptation measures with regard to the possible vulnerabilities.	Work done on this in the USA with regards to hydrodynamic bridge design. TRL undertook work in the Futurenet project[28] for road and rail. A good resource would be some sort of database of adaptation measures, e.g. porous pavements. The CEDR ROADAPT project also has a database of adaptation measures.

[28] https://www.horizon.ac.uk/project/futurenet/

TARGET	PROGRESS
Development of adaptation strategies and their implementation for existing infrastructure.	ROADAPT has done some work on that topic as well.
TECHNOLOGY PROVING	
Optimisation of identified adaptation measures and further development to enable deployment.	Examples are in the project list
Selection of infrastructure elements (e.g. structures, drainage elements as well as road pavement) for pilot applications.	Examples are in the project list. New drainage models have been trialled, and SUDS drainage implemented. The CEDR project WATCH is producing guidance on water management.
Single technology proving of selected adaptation measures/technology.	There have been trials of porous and reservoir pavements in the UK and France.
Validation of technologies based on the results of pilot projects.	ERA-NET Plus Infravation programme

Table 2: Progress against Milestone 1 Targets

4.2 MILESTONE 2: ACHIEVING RESILIENT SECTIONS OF THE TEN-T NETWORK (2020)

By 2015, validated information on the adaptation technologies available was largely provided. Unified information on regional climate change effects, as well as the scenarios relevant for transport infrastructures, are available. Validated methodologies for the identification of vulnerabilities will have been proven. Moving to 2020, there will be greater emphasis on the deployment of adaptation measures on the corridors; key elements to be developed are:

Corridor and sub-system proving

- Implementation of climate resilient technologies will be undertaken on three pilot TEN-T corridors or sub-systems such as city ring roads and transport interfaces;
- Agreement on common specifications for identified routes;
- Application of risk-based methodologies for assessing the vulnerabilities of the three selected corridors/sub-systems (identification of hot spots; modification of adaptation strategies).

Technology proving

- On-going research on additional potential technical solutions;
- Real-time traffic management systems that monitor traffic and environmental conditions and provide an early warning of trigger events;
- Improved weather and traffic prediction models;
- Enabled technology on a systems level (i.e. integrated over materials and components, management strategies and policy and governing principles);
- Undertaking of cost-benefit analyses; evaluation on the sub-system level, including consideration of social implications of technologies applied on the pilot corridors;
- Allied to the technical tasks, there should be the development of new national level management and governance processes.

Multimodal integration

- Implementation of methodologies on TEN-T corridors of other modes;
- Common development of adaptation measures especially regarding flooding;
- Identification and update of all guidelines and standards (of all modes) with regard to the climatic conditions taken into account.

4.3 MILESTONE 3: ACHIEVING RESILIENT TEN-T NETWORK (2025)

It is expected that all technical solutions will have been tested and validated on sub-system level; cost-benefit analyses will have been carried out. The key task of milestone 3 is the implementation of all technologies on system level (three TEN-T pilot corridors).

By 2025, all technologies for resilience should have been proven on a European scale, including sub-systems identified by 2020. At this stage, there will be a requirement to take best practice from the three routes, learn and improve and continue to deploy solutions more widely across the TEN-T network. From this point, technologies, operational strategies and governing principles will be fully integrated.

Underpinning this will be the development of governance and management systems with an overview at a European Union level; these will be founded on risk-based asset and accessibility management. Allied to this will be transport and asset management strategies at a European level with affiliates in Member States.

4.4 ROLL OUT: 2025 AND BEYOND

By 2025, the methodologies and technologies will have been demonstrated on live roads and will be ready to implement. As various National Road Authorities will have been involved in the programme, the process of dissemination and implementation will already have begun in earnest. Further implementation by Member States will continue after this time. The research will not stop in 2025, as systems and technologies will be improved and refined and have additional features added.

5. REFERENCE TO NATIONAL PROGRAMMES

In delivering the FOR Programme, co-operation will be sought with a number of 'sister' National Programmes[29] with shared aims and goals, as well as research projects undertaken by FEHRL members and partners. It is envisaged that there will be a two-way exchange of ideas and information on Work Packages, as well as the sharing of research expertise, test facilities and demonstrators. Furthermore, there will be a need to validate results and test interoperability, which will require co-operation across equipment and product manufacturers and infrastructure owners. The sister programmes that are already under development and with which co-operation will be encouraged are described below.

5.1 ROUTE 5ÈME GÉNÉRATION – R5G (THE 5TH GENERATION OF ROADS) - FRANCE

In synergy with the FOR Programme, FEHRL's French member IFSTTAR has launched the *"5th Generation of Roads"* programme, which aims to design full scale demonstrators integrating the numerous innovations already available within research centres, and demonstrating the synergies among them.

Specifically, there is work being undertaken on areas that are relevant to the resilient road, such as trials on heating and cooling pavements including porous asphalt and energy generation from the pavement using photovoltaic technologies.

5.2 STRASSE IM 21. JAHRHUNDERT (ROAD IN THE 21ST CENTURY, R21C) – GERMANY

The objective of the German research programme "Die Straße des 21. Jahrhunderts" (Road of the 21st Century) is to further develop the road in a functional way.

[29] http://www.foreveropenroad.eu/?m=19

Based on future requirements and new challenges, seven thematic priorities were established, of which one area (safe and reliable roads) has a specific relevance to the Resilient Road, as follows:

The network elements which are especially important for the quality of traffic will be subject to in-depth safety management. All major routes are to be provided with optimum protection against the impact of climate change, and the routine road maintenance services will be equipped to cope with extreme weather events.

5.3 THE E39 COASTAL HIGHWAY ROUTE– NORWAY

The route runs from Kristiansand in the south to Trondheim in the north, and is approximately 1,100 km long. It is estimated that the required investments and improvements between Kristiansand and Trondheim will cost about € 40 billion.

Travel time today is around 21 hours and requires the use of seven ferry connections. The aim is to create an improved E39 road without ferries, which will reduce travel time to around 11 hours and the distance by around 50 km.

The aim is to look into what such an improvement will mean for trade and industry, as well as for settlement and employment patterns in the affected regions. The project includes tasks such as evaluating different technological solutions for fiord crossings, and assessing how technical installations in connection with these crossings may be utilised to harness energy from wind, waves and current. A key consideration of the project is the environmental aspects both during construction and operation including:

- Resilience to the possible consequences of climate change and the extreme fjord crossings;
- Innovative material and structures (more durable and less material use);
- Energy-efficient roads including energy harvesting;
- Reducing emissions for operation and maintenance;
- Reducing environmental impact (biodiversity, noise, air quality etc.);
- Reducing emissions by road design.

5.4 EXPLORATORY ADVANCED RESEARCH PROGRAM (EAR) – USA

Exploratory advanced research focuses on long-term, high-risk research with a high payoff potential. It matches opportunities from discoveries in science and technology with the needs of specific industries. There are a number of early technologies underway that support the general aims of the resilient road, such as cementitious composites for crack-free pavements and structures, novel binders and structural health sensors.

5.5 CLIMATE PROOF NETWORKS – RIJKSWATERSTAAT, THE NETHERLANDS

In the Netherlands, there are several initiatives focused on the climate resilience of the infrastructure networks managed by Rijkswaterstaat. These initiatives follow on from policy, but also the FEHRL and CEDR initiatives in this field and clearly from the need that occurs from observed extreme weather events like the heavy showers in the summer of 2016.

There is a need to integrate these initiatives, resulting in a plan to define a Rijkswaterstaat commission for climate proof networks.

The objectives are to survey the risks for the functioning and performance of the networks imposed by climate change and define the level of required performance.

The approach will be on a strategic, tactical and operational level.

5.6 SUPPORTING PROJECTS

A number of projects which support the aims of the Resilient Road element have been identified from various sources, including the FEHRL and FOR websites and national projects identified by FEHRL Research Coordinators. Figure 4 below presents these projects against the innovation themes and it is noticeable that all innovation topics have some projects which address their aims, but they are unevenly spread. Summary details of a selection of representative projects are presented in Table 3.

THE RESILIENT ROAD															
Vulnerability Assessment									Geotechnics				Road Pavements		
KEYROADS	SWAMP	ADVIS RIVA	RAIN-EX	ALTRAIN	SERON	ROADAPT	INTACT	SECMAN	PANDA DEVICE	MATOSOL	CARACEC	ADSVIS	ROSANNE	WATCH	PAST

THE RESILIENT ROAD														
Management Strategies									Bridges and Tunnels				Governing Principles	
ADSVIS	DESIGN STANDARD	ROAD DES'N	SYSTEMS	INFREALERT	RESILIENS	ROADAPT	DETECTOR	SKRIBT / SKRIBT +	EXPANSION JOINTS	HEIJMANS BRAINJOINT	SKRBT / SKRIBT +	PHOTOPAQ	DEVELOPMENT	OASIS

Figure 4: Projects identified against innovation themes of the Resilient Road

DESIGN STANDARDS

The Netherlands have developed design standards for extreme weather condition resistant road design

INTACT - http://www.intact-project.eu/

INTACT brings together innovative and cutting edge knowledge and experience in Europe in order to develop and demonstrate best practices in engineering, materials construction, planning and designing protective measures as well as crisis response and recovery capabilities. All this will culminate in the INTACT Wiki.

Framing and Perspectives
Establish an in-depth appreciation of the interface between Critical Infrastructure and Extreme Weather Events and develop a comprehensive understanding of the current state of the art, and provide contextual guidance and theoretical underpinning

Climate and Extreme Weather
Collect and analyse trends, patterns and tendencies in extreme weather.

Vulnerability and Resilience of European Critical Infrastructures
Develop a methodological framework for CI vulnerability assessment and an analysis of CI protection measures.

Risk and Risk Analysis
Develop methodology and tools for risk management, and indicate gaps in risk modelling and data availability and seek for approaches and alternatives to close gaps.

ROADAPT, DETECTOR, WATCH (resulting from CEDR calls 2012 and 2015)
http://www.cedr.eu/strategic-plan-tasks/research/cedr-call-2012/call-2012-climate-change-road-owners-adapting-climate-change/

Risk-based approach addressing causes, effects and consequences of weather related events to identify the major risks that demanding mitigating measures from road authorities. An initial framework for this had been prepared through the RIMAROCC framework (Risk Management for Roads in a Changing Climate). ROADAPT has further developed this framework into practical and useful methods for road owners and road operators.

Detector – Decison Support Tools for Embedding Climate change Thinking of roads
- Economic Costs associated with integrating climate change into decision making
- Embedding climate change practice and procurement

WATCH - WATer management for road authorities in the face of climate Change
- Developing a transnational approach to water management in the face of climate change

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RESILENS - Realising European ReSiliencE for CritIcaL INfraStructure
http://resilens.eu/

The RESILENS project aims to further significant advancements in the resilience of critical infrastructure. The project will develop a European Resilience Management Guideline (ERMG) to support the practical application of resilience to all critical infrastructure sectors. Accompanying the ERMG will be a Resilience Management Matrix and Audit Toolkit which will enable a resilience score to be attached to an individual critical infrastructure, organisation and at different spatial scales which can then be iteratively used to direct users to resilience measures that will increase their benchmarked future score. Other resilience methods including substitution processes and measures to tackle cascading effects will also be developed.

AdSVIS - Adaptation of road infrastructure to climate change
http://adsvis.de/index.php?option=com_content&view=featured&Itemid=243&lang=en

The objective of this programme is to make Germany's main road connections more resilient to the impacts of climate change by 2030. 15 AdSVIS subprojects identify relevant climate-related impacts, assess the vulnerability of individual road infrastructure objects and develop adaptation measures.

1. "Risk analysis of key transit axes of the federal road network in the context of climate change" (RIVA) is the central project of AdSVIS
2. Analysis of climate change effects on road operations
3. Assessing the dimensioning of drainage for climate changed induced temperature and rainfall events to 2100
4. Development of a model to assess landslide risk areas and creation of a national hazard map
5. Study to review standardised asphalt pavements under changed temperature boundary conditions
6. Projected climate change and design of road constructions
7. Comparison of meteorological parameters at federal roads with grid data of climate projections
8. Development of climate impact models and design parameters for bridge and tunnel construction
9. Networking and communication of the research

Rain-Ex - Risk-Based Approach for the Protection of Land Transport Infrastructure against Extreme Rainfall
http://www.rainex-project.eu/

This project will advance the design of new land transport infrastructure towards a risk-based approach with regard to security aspects caused by rainfall-induced natural hazards. It will also develop a comprehensive approach for a risk-based assessment and adaptation of existing land transport infrastructure and foster the awareness of infrastructure owners and operators towards a risk-orientated mindset on security to ensure network availability. Dissemination and implementation of the envisaged methodology will be achieved via a user-friendly handbook.

ALLTRAIN - All-Hazard Guide for Transport Infrastructure
http://www.alltrain-project.eu/

This project aims to develop a comprehensive and structured all-hazard guide for critical transport infrastructures in Europe. The final guide enables owners and operators of transport networks to identify the relevant threats for infrastructure and the types of infrastructures susceptible to a specific threat. This approach supports the prevention and preparedness of critical infrastructure by stimulating and supporting risk assessment and developing methodologies for the protection of critical infrastructure.

SeRoN - Security of Road Transport Networks
http://www.seron-project.eu/

Development of a European procedure for the identification and designation of European critical infrastructures (ECI) and the investigation of cross-border impacts in case of disruption or destruction of critical infrastructures.

SecMan - Security Risk Management Processes for Road Infrastructure
http://www.secman-project.eu/

SecMan aims to develop a practical process for the identification of critical infrastructures in Europe. Furthermore, the assessment of these infrastructures in a structured and comparable way as well as the determination of effective protection and mitigation measures is foreseen. The methodologies will be summarized and combined into a comprehensive best-practice manual which allows for a trans-national structured and holistic security-risk-management approach.

The **FOX** (Forever Open Cross (X) Modal Infrastructure and **USE-iT** (Users, Safety, Security and Energy in Transport) and **REFINET** projects have identified a significant number of technologies addressing a wide range of issues, of which some are directly related to increasing the resilience of infrastructure such as improved inspection measures, advanced construction and durable material measures.
www.useitandfoxprojects.eu / www.refinet.eu

The Hampton Roads Climate Impact Quantification Initiative (HRCIQI) is a multi-part study sponsored by the U.S. Department of Transportation (DOT) Climate Change Center with goals that include developing a tool that provides methods for voluntary grantee consideration of financial impacts in infrastructure planning due to climate change and severe weather. This Baseline Study, conducted in collaboration with several DOT modes, and based on extensive consultation with regional governmental, military and industry stakeholders, summarizes available data, tools and methodologies to inform a robust analysis of the economic impacts of climate change and severe weather-related disruptions on the region's transportation infrastructure. DOT chose to study the Hampton Roads region based on its unique attributes, including its: extreme vulnerability to sea level rise impacts that is beginning to threaten the transportation system and military operations; strategic significance as home to the nation's largest concentration of federal facilities, including the world's largest naval station; and the partnership opportunities afforded through the Intergovernmental Pilot Program and its partner's deep expertise in analysing and addressing these impacts. DOT is intending to conduct follow-on work building on this Baseline Study.

There is a currently unfunded development task (Transportation Climate Impact Quantification Initiative) that has the objectives of quantifying the cost of climate change impacts to transportation and pilot new transportation resiliency tools at a regional scale to foster effective planning. This initiative will address the gaps in data and tools by supporting development of a comprehensive "transportation climate adaptation cost model" that provides methods for:

- Assessment of prospective financial impacts, beyond the baseline cost of the "state of good repair," in the Department of Transportation infrastructure planning and grant decisions due to climate change and severe weather;
- Science-based implementation of the Federal Flood Risk Management Standard (FFRMS); and
- Proactively prioritising and managing the Department's facilities to address Executive Order 13653 Preparing the United States for the Impact of Climate Change on climate adaptation/resiliency.

The intended outcome is a methodology for a quantification tool for use by government, industry and the public to make planning and funding decisions to address transportation infrastructure resiliency and future losses from sea level rise and extreme weather. It also supports coordinating with the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Planning Pilot Project (Hampton Roads Pilot).

The CEDR 2015 climate change call 'From desk to road' focuses on implementation and applicability, following the results of the CEDR 2012 call – Roadapt project. The WATCH project has started in 2016.

The objectives of the project are:

- Developing a manual to determine current and future resilience of the National Road Authorities approach to water management, ensuring optimal maintenance planning and asset management.
- Providing easy access to climate data tailored to determining resilience and providing guidance on how to use these data, plus developing a simple tool to show climate analogues for rainfall extremes.
- Gaining insight in the application of SuDS (Sustainable urban Drainage Systems) for storage and cleaning of excess water.
- Gaining insight in the alternatives to the costly retrofitting of existing drainage systems.
- Enabling informed decision making on water management, supported by cost-benefit analysis.

6. DEMONSTRATION PROJECTS

As the FOR Programme moves from concept to development, there is an interest in identifying demonstration projects that show at field or operational levels single technologies that support the aims of this roadmap. Certain projects have been identified below, with more to be added in the coming years.

In the Netherlands, the ROADAPT methodology has been tested and compared with the FHWA methodology in the InnovA58 project. Results will be reported in 2017, and will be an example for more projects. As part of the Rijkswaterstaat programme Climate proof networks, it is expected more demonstration projects will be possible. This will be worked on in 2017.

In Lithuania, they have developed a Test Road of Experimental Pavement Structures (REPS). REPS is a living lab (real operated road instrumented with various sensors to monitor different pavements resilience to traffic loads and changing climate conditions), which is 710 m in length and consists of 27 short sections, constructed of different pavement structures. The outcome of the research in REPS is used to develop new pavement structure solutions that are more adapted to increasing traffic loads, higher temperature fluctuations and increased number of frost-thaw cycles. Lithuania has also modified a number of national standards as a result of the REPS findings.

Norway has instigated the Varsom service (www.varsom.no/en), which provides avalanche, landslide and flood warning levels and maps for the country, which is supported by the XGEO expert system (www.xgeo.no).

FEHRL has organised Technical Scanning Tours in the USA since 2010, including a number focussing on resilience and adaptation to climate change and extreme weather events, and in 2016 undertook a tour of South Korea and Japan on 'Infrastructure Resilience'. The tours are intended to facilitate the exchange of knowledge and partnership building between international organisations and the participating members of FEHRL. Linkages to possible demonstration projects involve consideration of areas such as:

- The use of earthquake, flood and drought warning systems, e.g. there is a potential to apply these technologies to other infrastructure such as tunnels in Europe and Australia. For example, countermeasures against sediment disasters and urban floods and the provision of information for safe evacuation. This includes developing danger detection systems using big data and smart phones, identification of debris flow precursors, development of rapid inundation warning information systems for users in underground infrastructure, and development of rainfall and inundation prediction information provision systems;
- Techniques for in-built robustness and redundancy of infrastructure, e.g. classifications of the extent of recovery and restoration required following an event;
- Rapid recovery in a cost-efficient manner based on existing and modified standards, and repair approaches;
- Technology approaches of water retention pavements and heat shield pavements in real life applications, as adopted in Japan. Similarly, there are opportunities to share initiatives such as roll out pavements, solar roads associated with FOR, and transfer knowledge between Europe, South Korea and Japan on these technologies.

7. CONCLUSIONS

This document provides an update to the original Resilient Road Roadmap first published in 2013 to take account of progress against milestone 1, provide research and implementation recommendations towards milestones 2 and 3 and give information about ongoing research projects that are working towards the aims of the Resilient Roadmap.

Moving towards 2020, there will be a move towards identifying existing and developing new demonstration projects of single technologies and of sub-systems from both FEHRL and external organisations. As this phase progresses, it is clear that an increasing number of external organisations such as civil engineering contractors will play an important role in the implementation of technologies developed as a result of the FOR Programme. Nonetheless, FEHRL will retain an important role in fostering cooperation between both FEHRL institutes and external organisations to develop ongoing research activities and in dissemination.

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Dr Markus Auerbach	BASt	Germany	Workgroup Co-Leader
Tadas Andriejauskas	VGTU	Lithuania	Core group member
Caroline Evans	ARRB	Australia	Expert Reviewer
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