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Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures

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transport infrastructures

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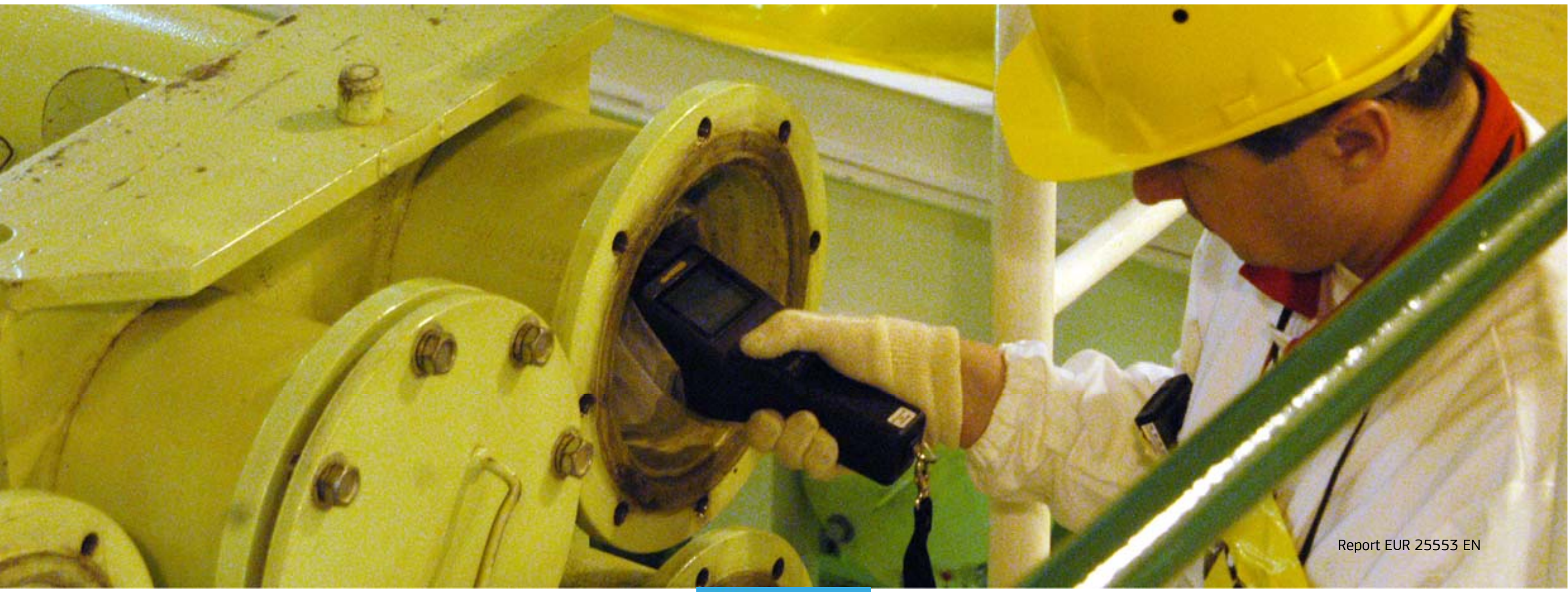

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Disclaimer

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1 Executive summary

This report provides a general EU-wide outlook about the future vulnerability of transport to climate change with a focus on the road and rail transport and their infrastructures. It also analyses some specific adaptations measures, illustrating key issues to be considered for policy making. It represents a first JRC/IPTS assessment of future impacts of climate change on the transport system in Europe, which has been conducted in the framework of the JRC PESETAII project.

Depending on future global warming and the region in Europe, transport modes and system components could be affected by one or several simultaneous changes in the climate conditions, including hotter summers, extreme precipitation events, increased storminess and sea level rise. If such impacts are not anticipated in future transport infrastructure design and maintenance, those changing weather conditions could, in some regions, accelerate their deterioration, increase severe damages risks, traffic interruption and accidents which could, on their turn, affect economic activities.

This research project has drawn some future trends regarding **changing exposure** of road and rail infrastructures to weather-induced risk under climate change, considering two future time intervals (2040-2070 and 2070-2100), and future **infrastructure deterioration and damage costs.** Costs associated with some selected **adaptation cases** were also assessed.

The overall assessment has made use of available climate models based projections (FP7 ENSEMBLE[1]), considering three distinct global emission scenarios (one medium scenario - A1B, one low emission scenario - E1 - and one high emission scenario - RCP8.5) and model realizations. A EU-wide technico-economic analysis has been applied by combining different types of spatial information, including:

- Climate data and climate stress factors representative of the different problems considered (e.g. rail track temperature, pavement temperature, and extreme precipitations).
- Transport information for EU27 (transport infrastructure, network, and transport activity): TRANSTOOLS model, TELEATLAS, GISCO.
- Physical information (e.g. sea level rise, coastal information (e.g. sea storm heights – DIVA database, hydrological data (JRC/IES), soil types (ESDB database).
- Engineering data and information about the underlying deterioration & damage mechanisms, maintenance practices and costs (mainly EU and US data sources).

1.1 Future impacts on road infrastructures

Construction design and maintenance of transport infrastructures are essential to maintain their integrity and serviceability. Nevertheless, complete avoidance of weather-induced infrastructure **deterioration and failures** is not economically feasible. Therefore, both average and extreme conditions currently represent a non negligible component of transport infrastructure costs. For road transport infrastructures, weather stresses represent from 30% to 50% of current road maintenance costs in Europe (8 to 13 billon €/yr). About 10% of these costs (~0.9 billion €/yr) are associated with extreme weather events alone, in which extreme heavy rainfalls & floods events represent the first contribution.

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[1] http://www.ensembles-eu.org/

This study concludes that, at EU27 aggregated level, compared to today, average precipitation-induced normal degradation of road transport infrastructures will only slightly increase in the future. However, more frequent extreme precipitations and floods (river floods and pluvial floods) as expected in different regions in Europe could result in an extra cost for road transport infrastructures (50-192 million €/yr for the A1B scenarios, period 2040-2100). Milder winter conditions are projected to result in reduced costs for road infrastructure (-170 to -508 million €/yr for the A1B scenarios). On the other hand, increasing average temperature all over Europe could require changes in maintenance operations and practices and represent extra costs.

These costs provide a highly aggregated overview of the possible trends for road transport in Europe. More severe consequences at local or regional level are not excluded, implying more significant additional spending to both repairing and maintenance of infrastructures, and, also, possible severe indirect consequences (e.g. fatalities due to extreme weather events). For instance, current and future patterns about extreme precipitation show a highly uneven spatial distribution.

1.2 Four vulnerability and adaptation case studies

Four case studies were selected in view of a EU-wide analysis about future exposure vulnerability and adaptation (Table 1), covering different aspects of climate change (extreme precipitation and floods, heat stress, sea level rise), infrastructure types (roads, rail track, bridges) and involved life spans (7 years to more than 100 years).

					Area for cost quantification		
Climate change effect	**Mode**	**Transport system component**	**Typical infrastructure life**	**Chapter in this report**	**Asset at risk**	**Adaptation**	***Avoided impacts***
Change in temperature	road	infrastructure	7-10 years maintenance cycle	Chapter 4	Mapping future changing risk for road pavemet cracking	changing asphalt binder	*- reduce road pavement degradation* *- avoid accidents (vehicle damages, injuries, fatalities)*
	rail	infrastructure and operation	50-100 years track life	Chapter 5	Mapping future changing risk for rail buckling	speed limitations changing track conditions	*- reduce rail track buckling damage* *- avoid accidents (vehicle damages, injuries, fatalities)*
Change in precipitation and river floods	road rail	infrastructure (bridges)	> 100 yr life	Chapter 6	Mapping future risk for river bridge scour	- rip rap, - strenghtening of bridge foundations with concrete	*- damages to bridges due to scour* *- accidents, fatalities*
Sea level rise and sea storm surges	road	infrastructure	.> 100 yr life	Chapter 7	Value of infrastructure at risk of permanent or temporary inundation	-	-

Table 1: Selected impacts and adaptation measures considered for quantified assessment

1.2.1 Exposure and vulnerability

For each of the four cases, the vulnerability is assessed with consistent risk indicators (7-day maximum pavement temperature, number of days exceeding critical thresholds considered for rail buckling risk, bridges exposed to 20%-40% increase in 100-yr river discharge, coastal infrastructure at risk of inundation. Geographical areas and infrastructures at risk – or **critical infrastructures** - under future climate change were then identified (see Figure 1, Figure 2, Figure 3). Depending on the impact category, the geographic distribution of future risk is more or less uneven. Altogether, such uneven patterns, uncertainty about future greenhouse gas emissions and significant variation across climate models represent an important challenges cost efficient adaptation strategy. For the case of transport infrastructure, this issue is particularly critical where long-live infrastructures are concerned (roads, bridges, sea ports…).

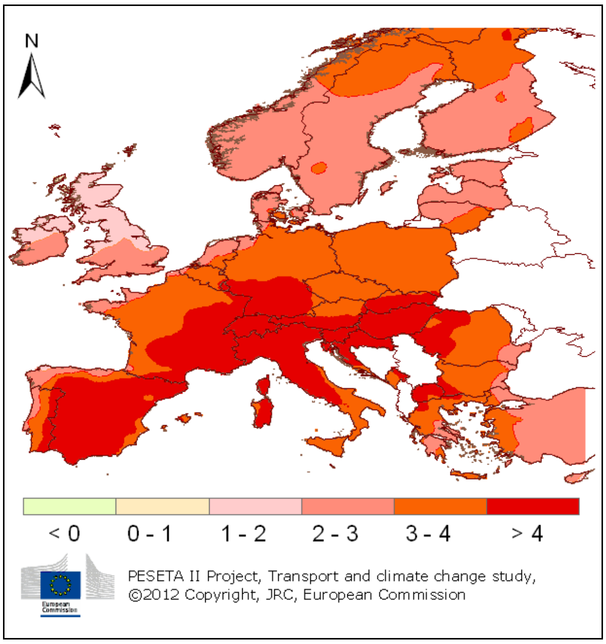

Figure 1: Vulnerability of road pavement to heat stress: Change in 7-day maximum pavement temperature in the different climate zones in Europe in the case of one A1B scenario (period 2070-2100 compared with 1990-2010)

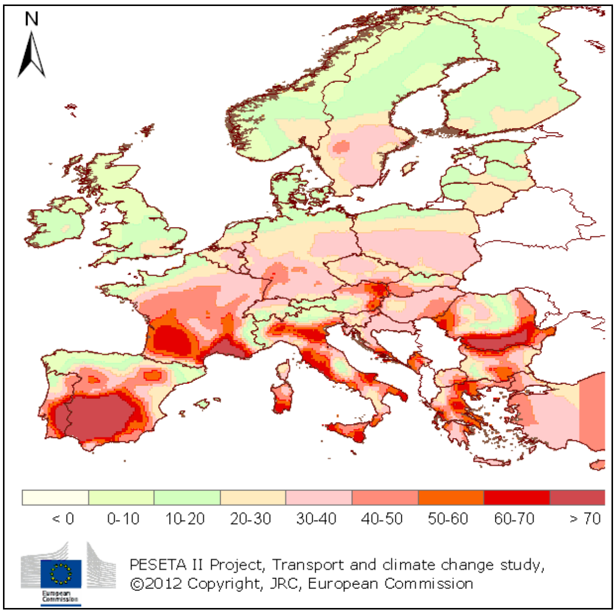

Figure 2: Vulnerability to rail track buckling: Number of days par year with Tmax exceeding Critical temperature (CRT70) in the case of one of the A1B, during 2070-2100 in addition to current situation (1990-2010).

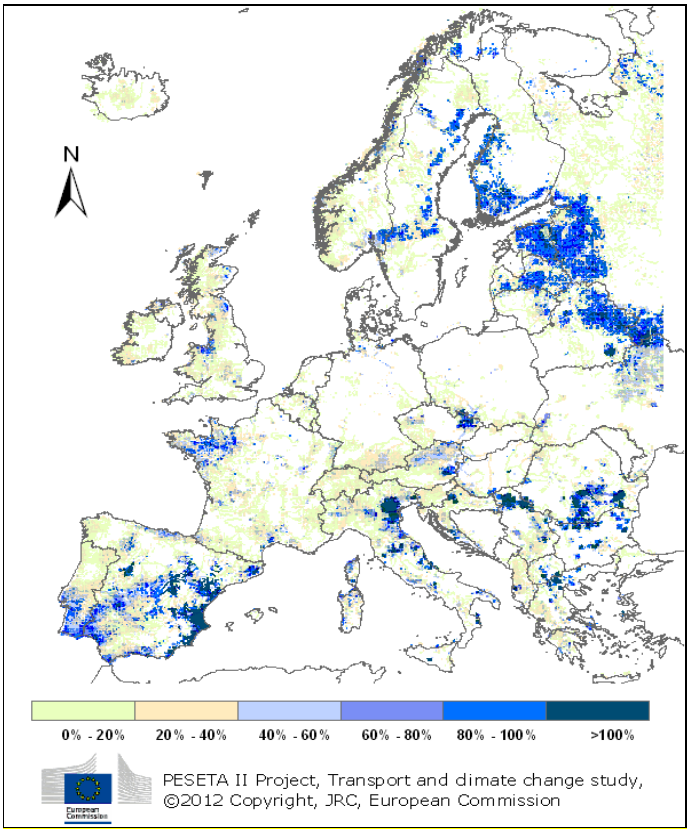

Figure 3: Vulnerability of bridges to scour risk – in the case of one of the A1B scenarios. Blue zones signal areas where river bridges could be at risk (percentage increase in 100-yr-return peak flow by 2070-2100)

This study has produced an initial estimate of **future risk of sea level rise** and sea storm surges on road transport infrastructure. This risk is mainly based on infrastructure settled in areas lying below a level defined by the sum of sea level rise (1 m) and 100-yr sea storm surge height. At European level, the so-defined road infrastructure at risk of permanent or episodic inundation represents 4.1% of the coastal infrastructure. The value of that infrastructure is estimated to ~18.5 billion €.

Both vulnerability and adaptation costs would need to be assessed under a much higher spatial resolution, more realistic method for simulating inundation processes. Due to these limitations, the assessed costs represent a very first input for subsequent risk analysis at EU-wide level and can't be interpreted as an adaptation cost.

1.2.2 Cost of adaptation

Table 2 summarises the main costs estimates (million €/yr over the period 2040-2100) for current deterioration, current and future extreme weather event damage costs for road infrastructure, and costs of the two adaptation measures on respectively road pavement and river bridges.

Road Asphalt binder adaptation is the least costly measure and, given the relatively short life cycle (~7 years), it is not expected to represent a major challenge for infrastructure planner.

	Current weather induced costs (million €/yr)		**Change in future weather-induced costs (million €/yr)**		**Future cost for adaptation (million €/yr)**		**Total estimated costs (million €/yr)**
	Weather-induced wear&tear	**Extreme weather damage costs**	**Weather induced wear&tear (reduced winter deterioration)**	**Extreme weather damage costs**	**River bridges scour protection**	**Road pavement (asphalt binder)**	
Alps	179	43	-6 - 0	3 - 11	16 - 19	3 - 4	16 - 34
UK & Ireland	2 213	59	-8 - -4	13 - 20	25 - 76	0 - 6	30 - 98
Eastern Europe	1 351	29	-44 - -4	3 - 9	29 - 39	16 - 61	5 - 105
France	535	133	-63 - -32	-4 - 29	34 - 73	6 - 15	-29 - 85
Iberia	369	86	-126 - -75	-2 - 5	41 - 45	10 - 15	-77 - -9
Mediterranea	4 038	53	-35 - -25	-2 - 3	52 - 57	9 - 11	23 - 47
Middle Europe	760	73	-201 - -27	13 - 37	27 - 32	9 - 57	-152 - 98
Scandinavia	959	153	-26 - -2	27 - 77	38 - 39	0 - 11	40 - 125
Total	**10 405**	**629**	**-508 - -170**	**50 - 192**	**262 - 381**	**52 - 180**	**-144 - 582**
% maintenance cost	*40.0%*	*2.4%*	*-2.0% - -0.7%*	*0.2% - 0.7%*	*1.0% - 1.5%*	*0.2% - 0.7%*	*-0.6% - 2.2%*

Table 2: Overview of current and future costs associated with impacts of climate change to road transport infrastructure and of costs of two adaptation measures (A1B scenario)

Protection of **river bridges** may be needed over the next decades for about 20% of the stock in order to mitigate scour risk associated with increasing river flood. Given that bridges are designed for long life spans (>100 years) and that their maintenance and repairing activities have to be planned long in advance, future climate-related risk should be included in corresponding prior cost-benefit studies. It has to be noted that in this study, only one particular climate scenario was considered, which may significantly underestimate the uncertainty about both the vulnerable bridge stock and adaptation costs.

Compared with maintenance costs, the adaptation costs estimated for the A1B scenarios (314-560 million €/yr) represent a small percentage of current road maintenance costs (1.2% to 2.2%). Damage costs which would be avoided by such adaptation measures could be several times higher. The cost of bridge failure could easily reach 2 to 10 times the cost of the bridge itself.

Such a comparison for the rail transport can't be made as rail infrastructure spending data are lacking. Above comments made for **river bridges** also apply in this case.

	Rail transport: adaptation costs (million €/yr)		
	River bridges	**Rail track buckling**	**Total**
Alps	4 - 5	1 - 1	5 - 6
UK & Ireland	6 - 19	0 - 1	7 - 20
Eastern Europe	7 - 10	4 - 6	11 - 16
France	8 - 18	4 - 5	12 - 23
Iberia	10 - 11	2 - 4	12 - 16
Mediterranea	13 - 14	6 - 13	19 - 27
Middle Europe	7 - 8	2 - 6	9 - 14
Scandinavia	10 - 10	1 - 2	10 - 12
Total	**66 - 95**	**25 - 48**	**90 - 143**

Table 3: Annual costs of two adaptation measures over the period 2040-2100 for rail infrastructures (A1B scenario)

Regarding heat-induced **rail buckling risk**, the most commonly applied adaptation measure (speed limits) results in trip delays. These were assessed to represent ~0.01% of current travelling time for passenger and freight transports and could be doubled or multiplied by four depending on the climate scenario (A1B or RCP8.5) over the period 2070-2100. Changing the track anchoring conditions (adapting stress-free temperature to higher summer temperatures) could help reducing these delays, but a detailed assessment would be needed to validate such an option and assess its costs.

1.3 Key messages

This research provides some orders of magnitudes about EU-wide future climate induced costs for transport and some adaptation measures.

It also illustrates the fact that each considered adaptation measure connects to highly specialised research fields and that its assessment hinges on considerable amounts of data of different types (climate change, engineering, transport network, transport modelling, spatial information analysis, micro- and macro- economic analysis).

The **uncertainty regarding climate data and climate model** projections is significant, especially when using extreme values (e.g. precipitation). This is critical especially where further modeling is needed (e.g. river floods), thus increasing the overall uncertainty.

Important **data gaps and uncertainties** also concern the transport system itself (examples are infrastructure stock, size, age and geographical distribution, maintenance costs, current vulnerability and deficiency, traffic, current maintenance practices – e.g. stress free temperature for rail track). Statistics about transport infrastructure weather-event damages are surprisingly missing for most parts of Europe, or at least not readily available.

Very low to moderate adaptation costs have been estimated in this study for the four case studies. More research and experience-based evidence would be necessary to provide a more comprehensive picture for all transport. The cost of adaptation could also be minimised by mainstreaming the climate dimension in future infrastructure planning and scheduled maintenance activities. With this respect, making **transport infrastructure climate resilient** is acknowledged in the Transport White Paper[2] as one of the condition to be fulfilled by future infrastructure projects: "*Co-funded projects should equally reflect the need for infrastructure that minimises the impact on the environment, that is resilient to the possible impact of climate change and that improves the safety and security of users*."

Data and methodological work will be needed to properly include that dimension in infrastructure project oriented **cost-benefit analysis**.

Two key aspects regarding the adaptation of transport infrastructure also emerged from the consulted literature and experts. On the one hand, disasters or damages currently incurred are often attributed to a **sub-optimal maintenance** and "old-fashion" maintenance practices could represent effective preventive measures (e.g. maintenance of culverts and drainage systems). On the other hand, the long life of transport infrastructures, combined with the uncertain future climate (over 20-100 years) complicates the decision making about adaptation strategy. On a case-by case basis, and when conducting cost-benefit analysis, two adaptation strategies could be envisaged:

- **Adaptive management** means that incremental adaptation is decided and implemented over successive short timescales (10 years for instance). The advantage is to manage climate change uncertainty iteratively, based on gradually increasingly reliable climate change, reducing the risk to commit to highly expensive investment which could tune out inadequate.
- **One-off adaptation** assumes that adaptation is undertaken once to deal with long-term.

The question to be addressed is also whether **construction design codes** need to be revisited in the light of climate scenarios and assessed risks (see for instance the case of bridge scour risk).

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[2] A Roadmap to a Single European Transport Area – Towards a competitive and resource-efficient transport system , (COM(2011) 144 final)

2 Introduction

This report provides a general EU-wide outlook about the future vulnerability of transport to climate change with a focus on the road and rail transport and their infrastructures. It also analyses some specific adaptations measures, illustrating key issues to be considered for policy making. It represents a first JRC/IPTS scientific contribution to the analysis of future impacts of climate change on the transport system in Europe, and has been produced in the framework of the JRC PESETAII project.

No EU-wide study was available when initiating this sector analysis. The first step for this research therefore consisted in a detailed literature review in order to:

- draw an overview of the expected impacts of climate change on the transport system,
- build an overall understanding on the multiple issues,
- assess the current transport vulnerability of transport to weather conditions,
- determine priority impacts and adaptation measures to consider for a quantitative analysis,
- design assessment methods,
- identify data needs and bottlenecks for Europe.

The question of whether climate change will significantly increase the different weather stresses to transport infrastructures and transport activities is a growing concern in the scientific literature and adaptation strategy reports. Important research efforts have for instance been conducted in several non European industrialised countries (e.g. New Zealand[1], Australia, United States – by EPA and by the US Department of Transportation[2]), and in European countries (e.g. UK program on Climate change[3]).

Based on this vast literature, and quantitative analysis, this study has developed an overview about the future vulnerability of transport to climate change, with a special focus on road and rail transport infrastructures. It has also analysed three adaptation measures concerning road and rail infrastructures and produced a first assessment of road transport vulnerability to sea level rise.

Chapter 3 reviews the types of climate impacts expected to increase weather stress to transport, possible risks and damages. It reviews and discusses recent assessment of the current vulnerability of transport to extreme weather conditions.
It also provides an outlook about plausible trends in climate changes as derived from available climate models and scenarios, possible consequences for transport and more particularly for road transport. The chapter then selects vulnerability and adaptation cases considered for the detailed analysis.

These are addressed in chapter 4 to 7. The first three chapters analyse adaptation measures associated with respectively road pavement, bridge protection, and rail track buckling. Chapter 7 provides a first order assessment of future risk for road transport infrastructure induced by future sea level rise and sea storm surges.

Chapter 8 then discusses these results altogether and draw general conclusions about adaptation for transport, data gaps and needs for future research.

3 Current and future vulnerability of transport to weather conditions

Transport of goods and passengers intrinsically hinge on a complex network of land based, inland water, maritime and air connections and infrastructures. The need to limit deterioration effects from adverse weather conditions (e.g. prolonged precipitation, heat stress, freeze-thaw cycle) and damages consequences in case of extreme events (e.g. embankment failure) is a key factor influencing construction designs . Weather contribution to the ordinary wear & tear of infrastructure and weather disaster risks are indeed intrinsic parameters for transport system design. Bridges over river for instance are usually designed to withstand 100-yr return river discharge. Transport conditions are also highly affected by extreme weather events such as winter storms, ice, and heavy rainfalls.

The two next sections concern the current vulnerability of transport to climate change and how it could change under future climate change.

3.1 Types of weather-induced impacts on transport

In general, transport can be vulnerable to many different types of weather conditions, of which, some of them could be exacerbated with climate change. Many of them relate to extreme weather conditions (e.g. storms, extreme precipitations, extreme temperatures) which on their turn may result in severe consequences for the physical environment (e.g. floods, landslides, avalanches,…) and represent risks for transport infrastructures and operations.

Based on reviewed literature, the study started with an exhaustive list of potential future impacts for transport (infrastructures / activities), linked to key weather stressors. All modes and components of the EU transport system (infrastructures, transport fleet, transportation operation and transport users) will, to a certain degree, be affected by extreme weather events. Some of such extreme weather conditions could be exacerbated under future climate change, thus increasing risks for transport and negatively affecting transport performance (safety, reliability, cost efficiency). Only few of the potential consequences could reveal positive (e.g. higher winter temperatures, opening of Nordic sea resulting from sea ice cover[3]).

Some consequences could partly counteract mitigation strategies (reduced river water depth could for instance induce lower energy efficiency of inland navigation, and even a higher frequency of navigation suspension).

Some effects will materialise through more frequent and severe transport service disruption (e.g. floods).

Table 4 provides a summary table about these impacts, with also an indication about the future trends in different parts of Europe. This preliminary overview has been based on scientific publications about main insights from FP6 PRUDENCE project[4] climate scenarios for Europe and other analysis concerning sea level rise and sea storm surges. As described in the table, the level of

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[3] A full analysis would still be needed to conclude on that

[4] http://prudence.dmi.dk/

uncertainty and availability regarding projected changes varies significantly among the different climate change stressors:

- The two main climate parameters which can be derived from climate model scenario and their regional downscaling concern **temperature and precipitation**.

- **Snow precipitations** are modelled but with lower reliability than precipitations. Due to increase mean temperatures in winter, it is expected that they will decrease in the long term. In the shorter term however, projections are highly model-dependent and showing contradicting trends in the medium time period (2030-2050)

Several severe events are associated with precipitation, although the causal relation can hardly be quantitatively assessed.

- The analysis of **River floods** in the framework of PESETAII (Feyen et al, 2012)[4] have been used as an input for the transport study (bridge scour case).

- **Flash floods**, as associated with heavy rainfalls (in case of thunderstorms for instance) are expected to become more frequent in certain regions of Europe. Extreme precipitation (~>50 mm/day) can be a proxy indicator for future trends in flash flood event frequencies.

- **Landslides** are the consequences of multi-factors, including soil moisture – as influenced by rainfalls intensity, soil types and slopes. As in the case of flash floods, heavy precipitations (e.g. precipitations more than 150-200 mm/24h) could only be used as a very rough proxy indicator to identify potential risks, in the case of mountainous regions.

So far, **wind gusts** are not properly simulated and for the purpose of this study, only few and regional studies could be referred to assess the vulnerability of transport.

Regarding **sea level rise**, The 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) projected that global mean sea levels would rise by **18–59 cm** above 1990 levels by the 2090s (where the lower bound corresponds to the lower estimate for the lowest emissions scenario, and the higher bound corresponds to the upper estimate for the highest scenario).

The IPCC also found that sea level rise could be greater than the global average around northern Europe, by an additional 15–20 cm due to changing climate patterns (air and water currents), reaching up to 38–79 cm around Denmark. Local SLR will actually vary depending upon ocean circulation patterns, gravitational effects, land subsidence or uplift along some coastlines, and other factors. Also, whereas sea level rise is already observed it can only partly be attributed to global human-created climate change. For instance, von Storch at al (2008)[5] argues that the main part of the increase observed in Hamburg is due to improved coastal defence. Another cause is the dredging of the shipping channel. These projections do not fully include contributions from the melting ice sheets. More recent studies (e.g., Rahmstorf (2007)[6], Pfeffer et al. (2008)[7]) suggest higher global sea level rise (**50-200 cm** above 1990 levels by 2100).

This general assessment of availability and/or uncertainty of climate data have been considered when selecting the areas for research and quantitative assessment.

Climate impact	**Overview of potential impact on transport system**	**Projected trends and magnitudes(*)**	**Regions / Seasons with good inter-model consistency(*)**	**Remark on general inter-model consistency and confidence level (*)**
Increased Summer **Temperatures**	Asphalt rutting, rail track buckling, change in required airport runway length, low water levels for navigation, thermal expansion of bridges, overheating of diesel engine	Increase in frequency, intensity and duration of heat waves over all Europe. Increase in inter-annual variability and changes in cold and warm extremes larger and faster than the corresponding changes in mean.	All	Consistency accross models
Increased Winter **Temperatures**	Reducing constraints for road and rail maintenance, Changed construction seasons			
Increased **Precipitation** and **floodings**	Flooding of land transport infrastructures, wet pavements and safety risks. Embankment collapse, bridge scour, flooding of underground transist systems. More frequent slushflow avalanches, landslides and associated risks.	Winter seasons: increased precipitation projected in 45º North regions, while southern regions would experience less precipitation.	Winter, All regions	Consistency accross models
		In summer, Nordic countries would experience increased precipitations (10-25% increase of 5-day 100 yr Return values). In Southern regions (Iberian, Mediterranean regions) precipitation will likely decrease. For the intermediate regions, trends are inconsistent across models (increase or decrease).	Summer: Nordic countries, Southern countries	Lower consistency (see intermediate regions)
Increased and more frequent **extreme winds**	Damage to infrastructure on roads, railways, pipelines, seaports, airports Cable bridges, signs, overhead cables, railroad signals, tall structures at risk Disturbance to transport electronic infrastructures, signaling, etc Reduced safety for vehicles driving	Expected increase of extreme wind speeds between 45º and 55º latitude, and especially in British Isles and North Sea coast during winter periods. Storms are likely to become more frequent in Central Europe. In other regions, no significant changes are projected.	Bristish Isles and North Sea costs	Low consistency, missing wind gust parametrization, missing observation data in many regions, weakness of models to reproduce available observed data
Sea Level Rise and sea storm surges	Erosion of coastal highways Higher tides at ports/harbor facilities low level aviation infratsructure at risk Regular and permanent inundation Bridge scour Corrosion	Sea level rise: Shoreline retreat everywhere, but magnitude depends on local morphology and (human induced) subsidence	NR	NR
		Sea storm surges: Height seems sensitive to sea level rise. Increase in storm surges projected along North Sea costs, especially German and Danish coast. Hamburg: increase of annual maximum water level by 20 cm.	North Sea costs, especially German and Danish coast	See wind extremes
Change in frequency of **Winter Storms**	Less or more snow / ice for all modes	Decrease in mean snow precipitation but more extreme snow precipitation in Nordic countries (see Makkonen et al, 2007)	?	Few studies on that
Permafrost degradation abnd thawing	Road, rail, airport, pipeline embankments failures	Thawing aleady observed and will contibue. Rhythm?	Nordic countries, Alpin regions.	NR
Reduced Arctic **sea ice Cover**	New northern shipping routes Reduced ice loading on structures, such as bridges or piers	No modelled-based projections	?	?
Earlier River **Ice** Breakup	Ice-jam flooding risk	No modelled-based projections	?	?

Table 4: Types of climate change impacts, possible consequences for transport and insight from climate change scenarios on regions affected and associated level of confidence.

(*) Based on Van den Brink et al (2005)[8], Frei et al (2006)[9], Von Storch et al (2006)[10], Fowler et al (2007)[11], Beniston et al (2007)[12], Rockel et al (2007)[13], Makkonen et al (2007)[14], Von Storch et al (2008)[15], Nikulin et al (2011)[16]

3.2 Current weather-induced costs for transport

As previously mentioned, weather is a major factor influencing the useful life of infrastructure and the transport safety. Maintenance and repairing transport infrastructures are indispensable to ensure their durability and the transport service that they can support. For instance, cold winter conditions and heat stress induce deterioration on e.g. road pavement and rail track that need to be routinely repaired. Such deteriorations affect the performance of the infrastructure together with other wear & tear factors, especially traffic load. Such repairing activities are part of the normal annual maintenance activities.
On top of the routinely applied maintenance activity, more profound repairing interventions (bridges repairs, slope stabilisation,…) are also required in case of severe damages incurred in case of extreme weather events. Both normal maintenance and repairing activities represent costs for the infrastructure owners (public / private) and a significant fraction of the total maintenance costs.

The two next sections review the literature to provide a general assessment about the overall contribution from weather stresses to the total maintenance costs for transport, and especially road transport infrastructure, which currently represents about 26 billion €/yr (IFT)[17].

3.2.1 Weather-induced infrastructure deterioration and extreme weather damages

Road, rail and other transport infrastructures are naturally exposed to various degradation factors (wear & tear). Traffic load and weather conditions represent two major causes of degradation. Other adverse factors include traffic accidents, robbery, construction defects. Reducing the level and the rate of these degradations by appropriate maintenance and repairing activities represents a cost for infrastructure owners (public and or private). Asphalt rutting, cracking, potholes, drainage system obstruction, are examples of weather-induced degradations which need to be taken into account in infrastructure design and maintenance operations.

Separating the two main factors for wear & tear (weather conditions and traffic) is rather difficult: asphalt rutting for instance is induced by high temperatures, but the effect is enhanced under high truck traffic load. While such combined effects are taken into account in detailed road deterioration models, such models, which are built upon detailed statistical information and regression functions can not be generalised for a large geographical region, and certainly not for Europe. Therefore, the faction of national aggregated maintenance costs attributable to weather can't be unequivocally assessed.

Dore et al (2005)[18] have analysed the contribution of traffic and weather conditions to the wear & tear of road pavement in Canada and reviewed similar information in other countries (Table 5). For Canada, the share for climate induced damages is in a 30%-80% range.

For US, based on two different sources, the % for highway is suggested to be lower (10%-15%) than for normal roads (up to 70%). The higher share for normal roads could be explained by the fact that highways are subject to more stringent designs.

For Australia a 35%-45% range is reported. For that country, precipitation-related costs and temperature-related costs account for 4% and 36% of current maintenance costs for roads respectively (Miradi, 2004)[19].

Traffic and weather contributions represent the bulk of road degradation. Considering a 30%-50% contribution from weather conditions for Europe would represent from **8 to 13 billions/yr** weather-induced costs for Europe**.**

References	$Ratio = \frac{\%Climate}{\%Traffic}$	Comments/Remarks
NIX, F. 2001. "Weight-Distance taxes". Prepared for Canadian Trucking Alliance, Nov 2001, p. 34.	50/50 to 80/20	• Research carried out in Canada • Damage type considered not mentioned
FEDERAL HIGHWAY ADMINISTRATION, 1997. "Federal Highway Costs Allocation Study". United States Department of Transportation.	10/90 to 15/85	• Research Carried out in United States • Climate effect more important for low volume roads (weaker structures) • Total costs considered as the performance parameter
SINHA, L. AND MCCARTHY, P., 2001. "Methodology to determine load- and non-load-related shares of highway pavement rehabilitation". Transportation Research Record, No. 1747, p.79-88.	72/28	• Research carried out in Indiana • Rehabilitation costs considered as the performance parameter • Least-squares models formulated by an aggregate approach
ST-LAURENT, D. ET CORBIN, G., 2003. "L'impact des restrictions de charge en période de dégel". Innovation Transports, numéro 18, pages 25-31.	30/70 to 70/30	• Ratios inferred from the study • Stronger structures (highways) barely sensitive to climate; weaker structures influenced by climate to various degrees • Fatigue damage considered as the performance parameter • Analytic-Empirical simulations calibrated on 9 sites in Québec
MARTIN, T., 2002. "Estimating heavy vehicles road wear costs for bituminous-surfaced arterial roads". Journal of Transportation Engineering, March/April, Vol. 128, No. 2, p. 103-110.	35/65 to 45/55	• Australian study on bituminous-surfaced arterial roads • IRI considered as the performance parameter • Climatic effects considered : thermal cracking and pavement deformation due to subgrade water content
TIGHE, S., 2002. "Evaluation of subgrade and climatic zone influences on pavement performance in the C-SHRP LTPP". Canadian Geotechnical Journal, Vol 39, p. 377-387.	60/40 to 75/25	• Ratios inferred from the study • Canadian study on pavements rehabilitated with overlays (24 sites, 65 sections) • IRI considered as the performance parameter • Ratios valid for wet low-freeze zones • Lower ratios found for higher volume roads and higher ratios found for lower volume roads • Hypothesis : fine subgrade are climate sensitive while coarse subgrade are not

Table 5: Role of climate conditions in road deterioration as compared with traffic contribution
Source : Dore el al (2005)

The decomposition of these annual costs between the different weather stresses and resulting deterioration and damages highly depends on the local conditions.

It is also impossible to reflect here on the details of deterioration types well known in road infrastructure engineering science. Such effects are documented in the specialised literature[20]. Even limiting the inventory to the bituminous road pavement case includes a variety of impacts (cracking, rutting, ravelling, pot-holing) and, within the category "cracking", distinction is made between transversal, longitudinal, crocodile cracking,….). In some cases, the effects can also result only indirectly from climate stressors. For instance, rutting effect in cold regions is aggravated by the use of studded tyres as used in winters, and also depends on the use of salt as a de-icing method[21].

In general, cold climate countries have to cope with pavement deterioration effects different from what warmer climate countries experience and practices are adapted accordingly. In countries such as Norway represent ~30% of the maintenance budget (PIANC, 2010)[22]. The US Federal Highway Administration (FHWA 2010) estimates the repair costs on its network caused by snow and ice at 5 billion USD annually.

While the "average" weather conditions represent continuous stressing factor for transport infrastructures, they can also be exposed to **extreme weather conditions**. Next section discusses the magnitude of damage costs associated with such damages.

3.2.2 Extreme weather events induced costs for transport

Extreme weather events represent an important influencing element in transport infrastructure design and transport management. Infrastructures are designed to cope with various stresses along their life, including extreme weather events as currently experienced. Transport services have also to be managed to reduce as much as possible disruption and maintain minimum safety standard in case of adverse weather conditions. Analysing, in a quantitative way, the current vulnerability of transport to extreme weather conditions in Europe is not a straightforward task. While countries such as New-Zealand and US tend to maintain centralised information systems on this field, this is mostly missing at a European level, and even not at national level.

In the case of extreme weather events affecting insured private properties (residential and commercial buildings) this information is to a large extent centralised by insurance and re-insurance companies. This is not the case for transport infrastructures that are funded by public money, and *de facto* insured by the taxpayer (Munich Re)[5].

In Europe, the FP7 WEATHER project has been a first attempt to estimate cost induced to transport by extreme weather events. In the case of road, the estimates were based on media reports on damages and transport disruption events associated with adverse weather conditions. However, only a limited number of countries (United Kingdom, Austria, Check Republic, Germany, Italy, and Switzerland) could be considered. Based on data from literature, the information was then further transformed into cost estimates, accidents, transport delays and derived costs were generalised to Europe by using scaling factors based on demographic parameters and climate indices. Similar efforts for the other modes were also conducted, resulting in more fragmented information.

Damages have been grouped in three main types of impacts: ice& snow, rain & flood, storms[6] and quantified for six elements of road transport system: Infrastructure assets, Infrastructure operations, Vehicle assets, Vehicle operations, User time costs and User safety.

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[5] Contacts made with the reinsurance sector (Munich Re)[5] to check the existence of such information.

[6] A total cost for heat and droughts is given a part (47 million €/year)

Damages to infrastructure assets and user operations (delays) constitute the most frequently reported incidents. Rainfalls (partly including local flooding) and storms (including storm surges) are the most relevant problem in road transport.

The total estimated cost is **2.25 billion €/year**, of which impacts on road transport represent 80% (1.805 billion €/yr). The impacts are dominated by rainfalls/floods (39%) and winter conditions (46%). Storms represent the third impact.

For **road transport**, impacts are dominated by damages to infrastructures (~80%), followed by transport user costs (11%). Again these impacts are mainly due to winter conditions (42%) and floods (45%).

	road	rail	maritime	intermodal	IWW	air	total	%
storm	174	3	20	1		155	354	15.7%
winter	759	52		0		147	959	42.5%
flood	822			0	5	60	886	39.3%
avalanche		6					6	0.2%
heat and dought	50						50	2.2%
total	1805	61	20	2	5	362	**2254**	
%	80.1%	2.7%	0.9%	0.1%	0.2%	16.0%		

Table 6: Current weather-induced costs (million €/yr) for transport (source: FP7 WEATHER project)

Costs are presented for seven zones characterized by broadly similar climate conditions (Figure 4). Estimated damage costs associated with adverse winter conditions are the highest in Scandinavia, Eastern and Middle Europe. Less surprising is the highest share of storms in Eastern Europe, thus lower in other regions (e.g. UK & Ireland). Southern regions in Europe experience the lowest amount of weather induced damages.

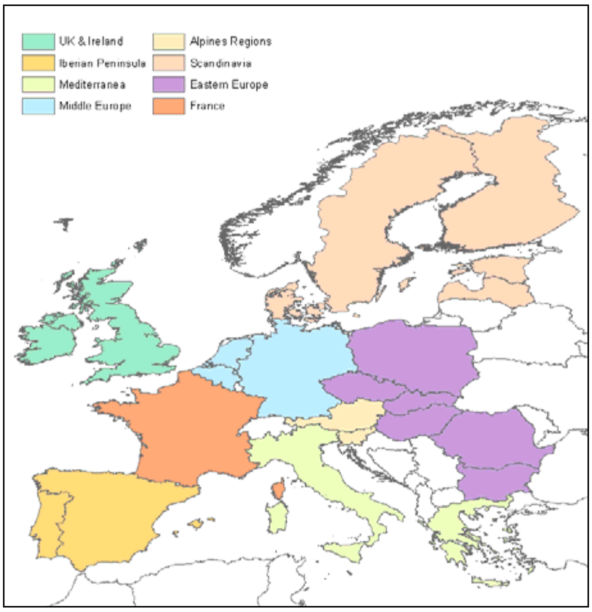


Figure 4: Climate zones in WEATHER project

The cost breakdown into transport element differs from weather category to the other. In all cases, costs linked to infrastructure assets are the most important (33% to 77% - floods). Costs for users are also significant (~16% across all modes, which the highest share for road transport - 11%). Ice and snow represent highly affects road safety.

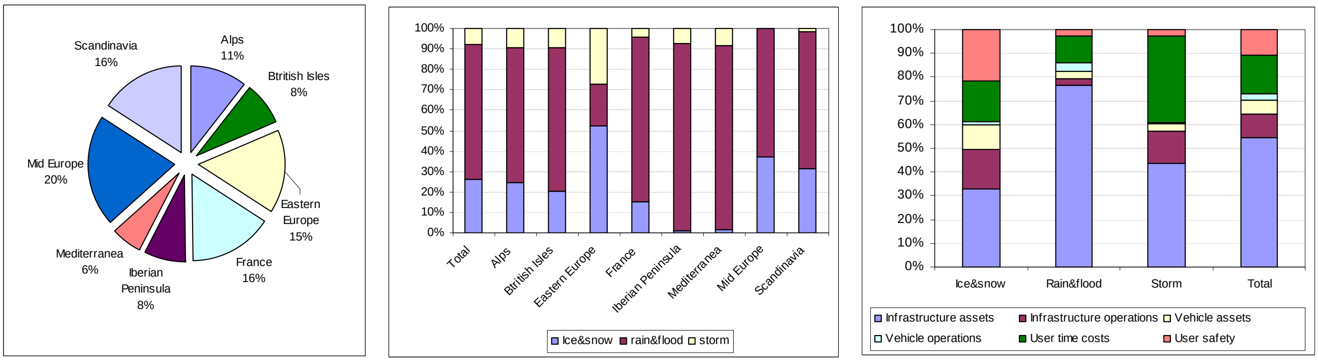


Figure 5: Current weather induced costs for road transport (total: ~1.8 billion €/yr)
Source : FP7 Weather project

Important remarks

Although, this first overview of weather induced costs for transport provides a useful insight about their magnitude, the results need to be interpreted with caution:

Geographical coverage

The analysis in the WEATHER project was primarily based on data from northern countries – thus possibly neglecting impacts from high temperatures. Large zones (France, Iberian Peninsula, and Scandinavia) are not covered by the media report review. Second, heat driven impacts are covered only in Germany, while this impact is not analysed for Italy.

Rainfall & Flood Impacts

In WEATHER, the category "floods" includes impacts from river floods, flash floods, heavy rains and landslides. This explains the fact that the estimated costs are systematically higher than the ones estimated for river floods only in the framework of the PESETAII project (Feyen et al, 2012)[4]. This comparison is made in Figure 6. The magnitude of the difference is very high (~one order of magnitude) suggesting that river floods costs represents only a minor fraction in these costs. This is in line with what other studies suggest. *Damages to streets and railways might be negligible in plain flood areas but should be included in **flash flood areas*** (Messner et al, 2007).

	flood costs (million €/yr)		
	infrastructure assets	total transport	river floods only (PESETAII)
AT	4	58	3
CZ	5	27	2
DE	113	145	9
UK	29	115	10

Figure 6: Comparison of "flood/rain" damages estimated in FP7 WEATHER with river floods damages (Feyen et al, 2012)

The case of Austria represents a specific case as the reviewed media reports concerned **landslides** events. Generalising these costs to Europe is thus tricky.

Winter impacts

The winter impacts are defined in association with frost periods, snow and winter storms. Frost periods and snow can not *per se* be defined as extreme weather conditions in many EU countries. Therefore, the estimated costs in that category mainly fall under the repairing costs of infrastructure normal deterioration.

Bias in media reports

Costs as derived from media reports might be biased by particularly severe events so that aggregated costs could be overestimated.

Delayed costs

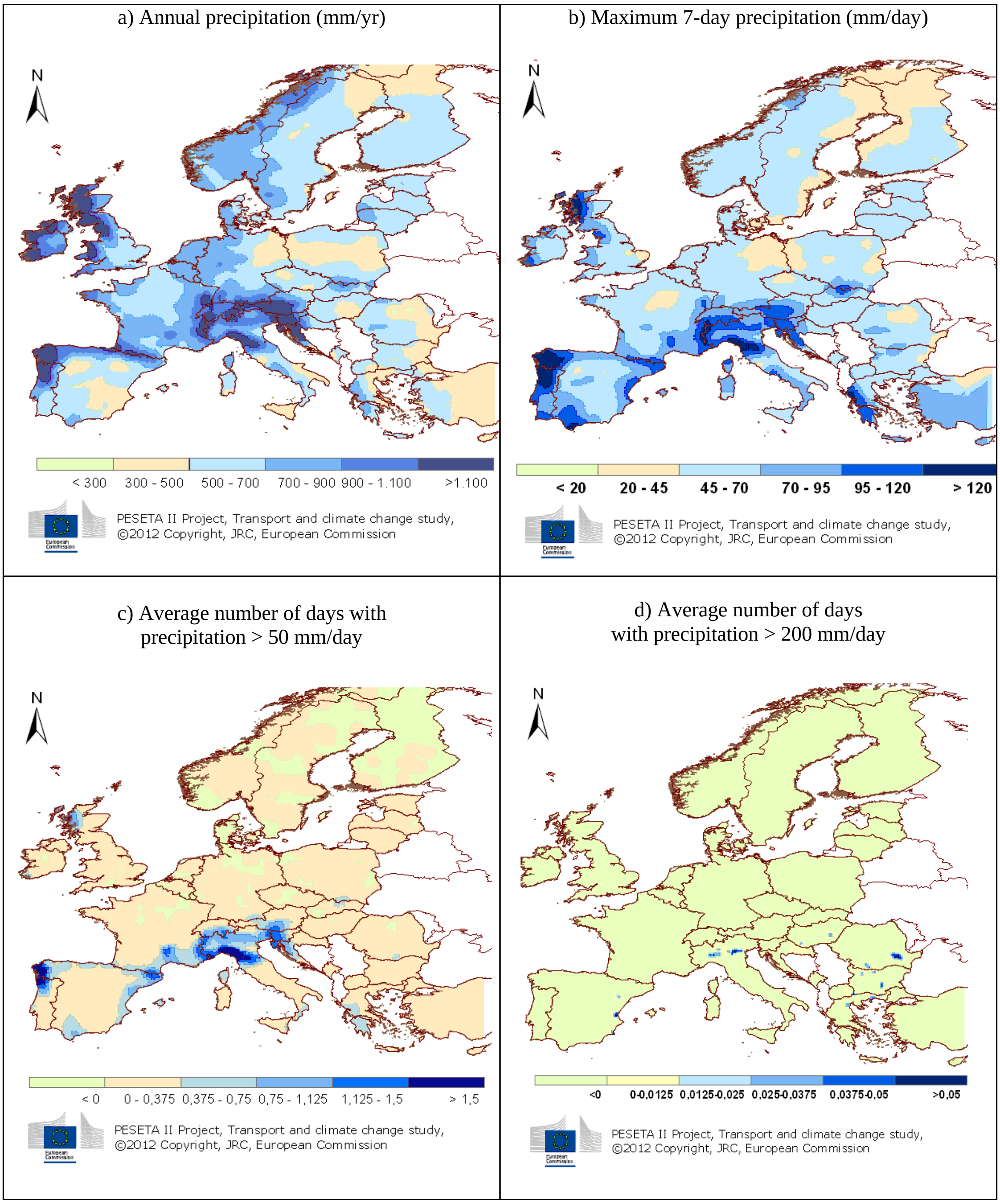
One difficulty intrinsic to such costs estimates is the fact that some parts of the costs are incurred later after the damage has occurred. In Australia for instance, the Queensland Government (2002)[23] estimates the damages by **floods**, including initial repairs to roads subsequent accelerated deterioration of roads (i.e. reduced pavement life) initial repairs to bridges (based on one-third of road damages) subsequent additional maintenance required by bridges. This suggests that the initial repairing operation represents 54% of the total cost (27% and 19% relate to the subsequent repair and maintenance for road and bridge respectively).

	cost per km of road indundated ($/km)			
	initial road repair	subsequent accelered deterioration of rods	initial bridge repair and subsequent increased maintenance	**total**
major sealed roads	34 860	17 430	11 985	**64 275**
minor sealed roads	10 895	5 450	3 815	**20 160**
unsealed roads	4 900	2 450	1 740	**9 090**

Table 7 Unit damages for roads and bridges (per km inundated) in Queensland, Australia
Source: source: Queensland Government (2002)

Climate index for cost generalisation to Europe

The generalisation of these media reports based cost estimates raised some difficulties. On the one hand, not all media reports provided a sufficient description of the weather conditions that led to the damages (e.g. precipitation, wind speed,…). The generalisation from country level damages to all Europe used a simplistic approach. For flood and rainfall impacts for instance, the generalisation was, to a large extent based on precipitation percentiles and/or frequencies for precipitation higher than 200 mm/day. This last climate index might be relevant for landslide events but flash floods may be better represented with 50 mm/day frequencies while river floods (in case of lacking simulation on river floods) might be best proxied with an index on prolonged intense precipitation (such as maximum 7-day precipitation). These indices are shown in Figure 7, together with the annual average precipitation.



a) Annual precipitation (mm/yr)

PESETA II Project, Transport and climate change study, ©2012 Copyright, JRC, European Commission

b) Maximum 7-day precipitation (mm/day)

PESETA II Project, Transport and climate change study, ©2012 Copyright, JRC, European Commission

c) Average number of days with precipitation > 50 mm/day

PESETA II Project, Transport and climate change study, ©2012 Copyright, JRC, European Commission

d) Average number of days with precipitation > 200 mm/day

PESETA II Project, Transport and climate change study, ©2012 Copyright, JRC, European Commission

Figure 7: Precipitation data for the period 1990-2010 (based on climate data from A1B-KNMI scenario)

A comparison between WEATHER cost estimates and reported infrastructure spending in the EU27 countries (IFT)[17] is made in Figure 8. This suggests that, at EU level, road infrastructure costs associated with extreme weather events represent ~ 4% of maintenance costs. Percentages at regional level vary between 0.5% and 13.2% but their reliability is limited by both the sources of uncertainties outlined in previous section and, the inaccuracy of maintenance costs.

The bulk of the weather-induced maintenance and repairing costs is thus associated with the gradual weather-induced deterioration discussed in previous section.

	Infrastructure spending (million €/yr)			Extreme weather-induced damages (million €/yr)					
	Total	Maintenance	Investment	Weather costs - rain	*of which river floods*	Weather costs - snow	total rain and snow	total	% maintenance costs
Alpines Regions	1 138	448	691	43	*4*	16	59	59	13.2%
UK & Ireland	12 942	5 534	7 408	59	*7*	17	76	76	1.4%
Eastern Europe	10 711	3 377	7 334	29	*20*	74	103	103	3.0%
France	12 835	1 338	11 497	133	*9*	25	158	158	11.8%
Iberian Peninsula	10 094	923	9 171	86	*7*	1	87	87	9.4%
Mediterranea	12 814	10 095	2 719	53	*13*	1	54	54	0.5%
Middle Europe	7 018	1 901	5 117	73	*13*	43	116	116	6.1%
Scandinavia	5 666	2 398	3 269	153	*7*	71	224	224	9.3%
EU27	**73 219**	**26 014**	**47 205**	**629**	***79***	**248**	**877**	**956**	**3.7%**

Figure 8: Comparison between estimated weather-induced costs for road transport infrastructures and maintenance costs – period 2006-2009 (million €/year)
Sourcse: Infrastructure spending (source: IFT), Non river flood costs (FP7 WEATHER project), river floods costs (Feyen et al 2012)

3.2.3 Key elements for vulnerability analysis for the transport sector

Analysing risk incurred by transport infrastructure should be performed for the infrastructure stock, taking into account age and expected residual life (of e.g. roads, bridges), projected change in exposure to risk (e.g. change in frequency / severity of extreme rainfalls), and risk of infrastructure failure. In reality, detailed and reliable data and infrastructure characterization at EU level is lacking to perform such a detailed and highly consistent analysis. The next sub-sections shortly discuss the relevant elements considered to develop a EU-wide first indicative assessment about future vulnerability of transport infrastructures.

3.2.3.1 Life span of infrastructures

Infrastructures are traditionally designed to cope with various stresses along their life, including extreme weather events as historically and currently experienced. Regular maintenance is normally performed to maintain sufficient resilience to the weather conditions. Design codes are usually defined to achieve a high level of resilience to extreme events for which the occurrences (return period) is set in accordance to the typical design life spans. For instance:

- Bridges: 100 yrs
- Roads: 30-40 yrs
- Road pavement: 10-25 yrs
- Culverts: 20-100 yrs
- Causeways in low-lying coastal zones: 20-100 yrs
- Drainage (surface): 20 yrs

Adequate accounting approaches are needed for cost estimates on long life infrastructures (see e.g. life cycle costs, discounting factors, depreciation factors) and appropriate harmonisation work will be needed in case of using data or results from the literature. This however is highly limited by the lack of EU-wide information regarding infrastructure age.

3.2.3.2 Thresholds

Existing research determines and refers to trigger points or thresholds above which the intensity of weather event is likely to result in damaging consequences and/or in transport disruption. Such trigger points have been derived in the research performed in New Zealand, US, and also compiled in the FP7 EWENT project[26]. Defining uniform thresholds over Europe is however mostly impossible because the design codes and local conditions are different. This is emphasised in the NZ study:

"We were unable to identify additional trigger points or elaborate on those identified for several reasons:

- *Details of infrastructure design standards and weather-related vulnerabilities were not readily available. For example, we identified the potential impact of extreme winds on the deflection capacity of cranes in ports, although* ***manufacturers' design standards*** *were not able to be identified within the scope of Stage One of this research.*
- *Design standards for short-life infrastructure such as bituminous road pavements vary according to* ***local conditions*** *and were considered to be adaptable to the predicted climate change induced conditions through regular revisions of design standards.*
- *Replacement costs if design standards failed were considered relatively low by industry leaders such as the NZTA.*
- *Climate change effects are predicted as long-term trends involving* ***short-term variances****. For example, mean temperatures are likely to gradually increase, although cooler years are also likely to occur within a long-term trend towards warming. Many of the predicted climate change effects are within the range of current climate variability, particularly in the short to medium term, and transport systems already have a degree of resilience to climate change effects."*

The study however concludes that *"Despite these difficulties, the concept of trigger points is considered to be an important link between asset resilience and weather stress, and a useful means of quantifying the scale of climate change effects. This concept will prove more useful when considering impacts at a more detailed level for different types of transport infrastructure in Stage Two or in the future Research."*

3.2.3.3 Response functions and thresholds

Each mechanism by which weather-induced deteriorations occur is specific to the infrastructure and, the level of deterioration, depends on a multiplicity of environmental parameters (e.g. locations, soil, traffic load,…). For instance:

- The scouring of bridges over passing rivers is determined by the velocity of water, river bed sediment type (sand or other) and the level of protection of foundations (e.g. rip-rap, reinforced foundations)[46]. It has to be noted that intensive research effort are still ongoing to fully understand and describe all the physical mechanisms and parameters in play[24].

- High temperatures can damage road asphalt by inducing cracking but this highly depends on the type of asphalt applied, and binder types used. Depending on weather conditions, countries in Europe already use different asphalts and asphalt binders.

- Heavy precipitations can result in road flooding, especially where culverts are not properly maintained.

In general, the various involved mechanisms can not easily be described by simple equations isolating one climate and/or biophysical parameter. This makes difficult to derive uniform damage functions over all Europe. In case of establishing damage functions, they may depend on a significant amount of local/regional specific parameters and assumptions (e.g. maintenance level, local conditions,…).

3.3 Future trends of climate stressors and consequences for transport

This chapter discusses plausible trends for vulnerability of transport to climate change, first regarding infrastructure degradations, second, extreme weather events.

It mainly focuses on road and rail transport and infrastructures. On the one hand, this mode is suggested to be currently the most vulnerable, especially to extreme precipitation and to winter conditions. Also, the other modes are shown to be vulnerable to winds and storms (e.g. aviation, maritime transport) for which climate models are the least robust. The most reliable climate trends concern precipitation and temperature.

3.3.1 Climate change scenarios

The future trends on future vulnerability of transport have been derived by making use of current vulnerability as assessed by the FP7 WEATHER project (see section 3.2.2) together with key climate drivers as projected by the climate models and scenarios considered in PESETAII and provided by the ENSEMBLE project[7] (as well as from the FP7 ClimateCost project). Three future climate change scenarios are considered. The A1B SRES scenario, the E1 scenario which broadly correspond to a 2ºC scenario and one of the new Representative Concentration Pathway (RCP8.5) scenario corresponding to a 8.5 W/m2 forcing by 2100. Driven by one of these emission scenarios, a Regional model combined with a Global Circulation Model (GCM) provides projections on climate conditions (e.g. temperature, precipitation,) for all Europe with a 25*25 km (or 50*50 km) resolution. Table 8 provides the list of considered combination of global warming scenario, driving GCM and regional models.

These scenarios were also used to subsequently analyse the adaptation case studies (chapters 4 to 7).

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[7] http://www.ensembles-eu.org/

Global emission scenario	Scenario	Institute	Regional model	Driving GCM	Used abbreviation in this report
A1B	A1B-KNMI-RACMO2-ECHAM5	KNMI	RACMO2	ECHAM5	A1B-KNMI
	A1B-METO-HadRM3Q0-HadCM3Q0	METO-HC	HadRM3Q0	HadCM3Q0	A1B-METO
	A1B-DMI-HIRHAM5-ECHAM5	DMI	HIRHAM5	ECHAM5	A1B-DMI
E1	E1-MPI-REMO_ECHAM5-r1	MPI	REMO	ECHAM5-r1 BC	E1-MPI-r1
	E1-MPI-REMO_ECHAM5-r2	MPI	REMO	ECHAM5-r2 BC	E1-MPI-r2
	E1-MPI-REMO_ECHAM5-r3	MPI	REMO	ECHAM5-r3 BC	E1-MPI-r3
RCP8.5	RCP8.5-DMI-HIRHAM5_ECEARTH_EC1	DMI	HIRHAM5	ECEARTH	RCP8.5-DMI

Table 8: Climate scenarios considered in PESETAII project

3.3.2 Weather-induced infrastructure degradation

In the following we discuss the three main deteriorating climate factors in terms of their future expected trend. The discussion focuses on paved roads which represents the biggest share of road network in Europe.

Precipitation-induced road degradation is assumed to be significantly aggravated where average annual precipitation increases by ~100 mm/day (Chinowsky et al (2011)[25], in which case road pavement may need to be adapted. This mainly concerns the weathering and ravelling effects on road pavement. Under the considered climate scenarios (A1B, E1, RCP8.5), such an increase in average precipitation not projected in any EU country by 2040-2070. By 2070-2100, such a change is plausible in several countries, but for one or two scenarios. This thus suggests that precipitation-induced road degradation could be slightly increased in some countries and that overall, the costs for Europe will not significantly change. It is also to be noted that precipitation is also involved in frost-induced degradation effect especially cracking and pothole effects (see winter conditions below),

Heat stress is particularly relevant for asphalt road pavement for which binder needs to be adapted accordingly. This specific case is analysed in more detailed in chapter 4. On the average, the relevant temperature index for that impact (7-day maximum temperature, see chapter 4) is projected to increase all over Europe. This indicates that heat-stress degradation will increase and that adaptation will be needed in the future. Similar conclusion can be made for rail track, which is analysed in chapter 4.

Winter conditions may severely affect the road pavement, and after winter season maintenance represents a high maintenance & repairing cost. The same holds true for rail tracks. Road pavement degradation models use the Freezing-Day index[8] as one of the main explanatory variable to simulate the cold climate contribution. It is projected to decrease all over Europe. The consequences of milder winters (also considering changes in freeze-thaw cycles and winter precipitations) is analysed in chapter 4.

Overall, it can be inferred that **weather-induced degradation could reduce if road and rail infrastructures are properly adapted to the increasing summer heat-stress.**

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[8] FDI is the sum of average daily temperature over the years, only including days with negative temperatures

3.3.3 Extreme weather-induced damages

This section discusses the question of the potential future changes in extreme weather induced risks for transport, and more particularly for road transport. As described in section 0, rainfalls (and consecutive floods) explain a large faction of extreme weather event induced costs for transport[9]. A rough outlook of potential future risks associated to these two categories of impacts can be produced by exploring the relevant climate indices derived from the different climate scenarios.

Regarding **precipitation**, literature shows that several categories of damages to road infrastructures can be related to distinct degrees of extreme precipitation (FP7 EWENT project)[26]:

- **50 mm/24h**: flooded roads, reduced pavement fraction
- **100 mm/24h**: the sewer system fills up; water rises up the streets from drains. Rainwater fills the underpasses and lower laying streets. Drain well covers may become detached and cause danger to street traffic. Reduced visibility, flooded underpasses
- **150 mm/24h**: road structures may collapse. Bridges may be flooded. Vehicle motors damaged and vehicle can be flooded. Roads might be covered by water or transported debris.

The maximum precipitation over a 7-day period may also represent a relevant proxy index for medium severity damages as induced by prolonged and intense precipitation.

The proxy climate index for future costs would thus depend on the damage category. Unfortunately the WEATHER data are not available neither per damage category (within the "flood & rain" category), neither at a more disaggregated level than the defined climate zones. We therefore base on two climate indices, namely annual number of days with precipitation higher than 50 mm/days, and maximum precipitation over a 7-day period (expressed as average daily precipitation) to infer a possible trend for future risks.

Table 9 shows the projected changes for these indices for the A1B scenarios and for the climate zones for which WEATHER data are aggregated. Average precipitation is also shown. As discussed in previous section, it projected to significantly decrease (Iberian Peninsula and Mediterranean countries) or only slightly increase in most part of Europe. Only Scandinavia, UK&Ireland and Middle Europe would, on the average, experience wetter weather conditions.

On the contrary, more frequent extreme precipitations events are projected all over Europe.

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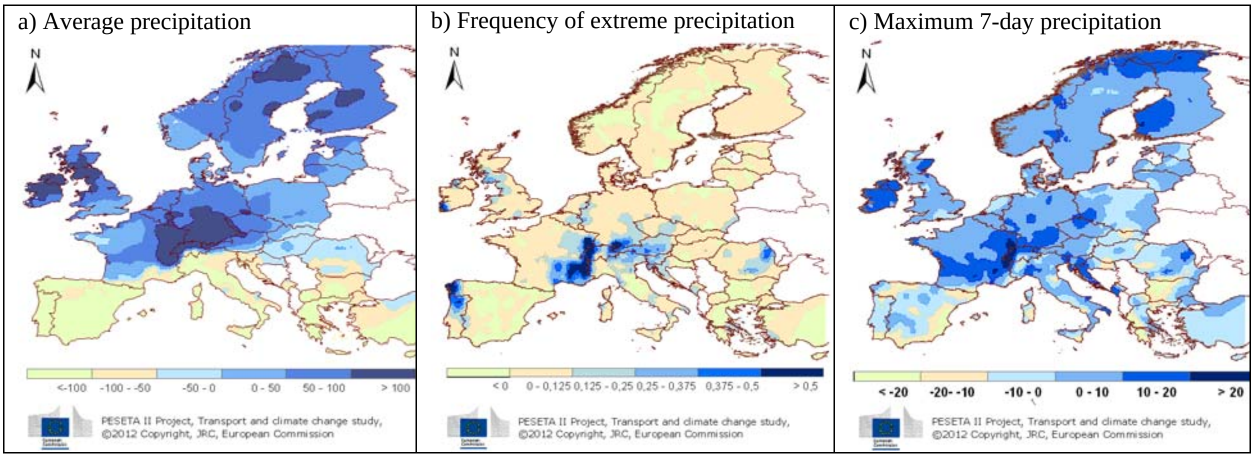
[9] As noted in section 3.2, the considered winter impacts category in the WEATHER project actually falls under the gradual deterioration classification is mainly address in previous section and chapter 4.

2040-2070	average			A1B-KNMI			A1B-DMI			A1B-METO		
	pavg	p50	pmax_7day	pavg	p50	pmax_7day	pavg	p50	pmax_7day	pavg	p50	pmax_7day
Alpines Regions	2%	26%	3%	3%	44%	9%	2%	15%	6%	0%	18%	-4%
UK & Ireland	3%	44%	8%	2%	38%	5%	3%	37%	8%	4%	57%	10%
Eastern Europe	1%	37%	1%	2%	30%	-2%	2%	22%	1%	0%	59%	4%
France	-3%	22%	0%	2%	38%	6%	0%	24%	4%	-12%	4%	-10%
Iberian Peninsula	-10%	5%	2%	-12%	13%	0%	-7%	10%	2%	-11%	-9%	4%
Mediterranea	-8%	3%	-1%	-7%	12%	1%	-7%	4%	-4%	-9%	-8%	-1%
Middle Europe	3%	65%	3%	7%	96%	5%	7%	63%	5%	-5%	35%	0%
Scandinavia	10%	50%	7%	6%	30%	5%	13%	92%	8%	9%	28%	9%

2070-2100	average			A1B-KNMI			A1B-DMI			A1B-METO		
	pavg	p50	pmax_7day	pavg	p50	pmax_7day	pavg	p50	pmax_7day	pavg	p50	pmax_7day
Alpines Regions	1%	39%	3%	3%	54%	6%	2%	16%	-1%	-1%	48%	3%
UK & Ireland	7%	80%	14%	9%	94%	10%	9%	64%	15%	5%	81%	18%
Eastern Europe	-1%	49%	1%	-1%	53%	-4%	1%	28%	0%	-3%	67%	7%
France	1%	43%	8%	5%	74%	13%	5%	34%	8%	-8%	20%	3%
Iberian Peninsula	-16%	15%	3%	-25%	3%	-10%	-14%	24%	1%	-10%	18%	20%
Mediterranea	-12%	7%	-1%	-15%	12%	-2%	-12%	9%	-5%	-8%	1%	5%
Middle Europe	6%	118%	6%	13%	230%	13%	8%	69%	6%	-3%	54%	1%
Scandinavia	17%	116%	13%	12%	127%	13%	24%	126%	14%	13%	96%	12%

Table 9: Change in precipitation regime by 2040-2070 and 2070-2100 as percentage of current situation for the 3 A1B scenarios (pavg: average annual precipitation; p50: number of days with precipitation > 50 mm; pmax_7day: average of the annual maximum precipitation over consecutive days)


a) Average precipitation

b) Frequency of extreme precipitation

c) Maximum 7-day precipitation

Figure 9: Change in precipitation regime by 2070-2100 in the case of the A1B-KNMI scenario: difference with current situation (pavg: average annual precipitation (mm/yr); p50: number of days with precipitation > 50 mm; pmax_7day: average of the annual maximum precipitation over consecutive days (mm))

The average of the relative changes in these two climate indices is used as a proxy of future damages for road infrastructure. These derived damage costs are shown in next table for the three groups of scenarios, showing a wide range of plausible changes and future costs.

Costs at EU level are expected to grow for the A1B scenarios for the two time intervals. The trend is however more ambiguous for some regions (Southern regions). The estimated costs also show a wide range of uncertainty associated with climate projections.

The EU aggregated costs for the first period are similar for the three types of scenarios. For the second period, the E1 scenario shows the lowest cost increase, while the RCP8.5 scenario projects the highest cost increases. This specific scenario would need however to be complemented with other model realisations to better represent the range of climate model uncertainties.

E1 scenarios	**1990-2010**	**2040-2070**		**2070-2100**	
	million €	million €	cost change in %	million €	cost change in %
Alpines Regions	43	42 - 48	-3% - 12%	42 - 49	-2% - 13%
UK & Ireland	59	65 - 75	10% - 28%	63 - 90	6% - 53%
Eastern Europe	29	30 - 35	2% - 20%	31 - 38	6% - 30%
France	133	132 - 148	-1% - 11%	119 - 138	-11% - 4%
Iberian Peninsula	86	75 - 86	-13% - 0%	72 - 81	-17% - -6%
Mediterranea	53	48 - 57	-9% - 7%	45 - 46	-16% - -13%
Middle Europe	73	55 - 101	-25% - 38%	65 - 88	-12% - 21%
Scandinavia	153	217 - 311	42% - 103%	205 - 266	34% - 74%
EU27	**629**	**663 - 861**	**5% - 37%**	**641 - 796**	**2% - 27%**

A1B Scenarios	**1990-2010**	**2040-2070**		**2070-2100**	
	million €	million €	cost change in %	million €	cost change in %
Alpines Regions	43	46 - 54	7% - 27%	46 - 56	7% - 30%
UK & Ireland	59	72 - 79	22% - 33%	82 - 89	40% - 52%
Eastern Europe	29	32 - 38	11% - 32%	33 - 40	14% - 37%
France	133	129 - 162	-3% - 22%	148 - 191	11% - 44%
Iberian Peninsula	86	84 - 91	-3% - 6%	83 - 102	-4% - 19%
Mediterranea	53	51 - 56	-4% - 7%	54 - 55	2% - 5%
Middle Europe	73	86 - 110	18% - 50%	93 - 162	27% - 121%
Scandinavia	153	180 - 230	18% - 50%	236 - 260	54% - 70%
EU27	**629**	**679 - 821**	**8% - 31%**	**775 - 955**	**23% - 52%**

RCP8.5 scenario	**1990-2010**	**2040-2070**		**2070-2100**	
	million €	million €	cost change in %	million €	cost change in %
Alpines Regions	43	56	29%	66	53%
UK & Ireland	59	74	25%	92	55%
Eastern Europe	29	39	34%	43	48%
France	133	156	18%	166	25%
Iberian Peninsula	86	85	-1%	91	5%
Mediterranea	53	59	11%	61	15%
Middle Europe	73	103	41%	127	74%
Scandinavia	153	219	43%	354	131%
EU27	**629**	**791**	**26%**	**998**	**59%**

Table 10: Plausible ranges for future costs (million €/yr) for road infrastructures due to floods&rainfalls for the different scenarios (own estimates)

3.4 Concluding remarks and selection of case studies

Transport infrastructure construction design, maintenance and repairing are essential to protect their structural elements against rapid weather-induced degradation and extreme weather-induced damages. This is a condition maintain transport users safety and service quality standards.
Nevertheless, infrastructure gradual degradation and risk of extreme weather induced damages can't fully be economically efficiently avoided. Today, for **road infrastructures**, both average and extreme conditions represent a non negligible costs (8 to 13 billion €/yr). Roughly 10% of these costs (~0.9 billion €/yr) are associated with extreme weather events alone, rain&floods representing the first damaging cause. This chapter has drawn some trends about the future weather-induced stress factors.

While precipitation-induced degradation may slightly increase in the future, milder winter conditions will contribute to decrease associated degradation. On the contrary, increasing average temperature all over Europe could require changes in pavement design and maintenance operations. Both consequences of milder winters and hotter summer conditions are quantitatively assessed in chapter 4. For the last case, the use of asphalt binder is analysed.

Plausible trends derived for future costs suggest that the most important damaging cause (rain & floods) will further increase in most parts of Europe. Estimated additional damage costs represent up to 1% of current EU27 maintenance costs (by 2070-2100 and higher GHG emission scenario).

The estimated costs provide a highly aggregated overview of the possible trends for road transport in Europe. Seen at a much more disaggregated level, they could represent more severe consequences for local and regional infrastructure owners and users. The future damages could indeed be very unevenly distributed spatially. Adding to this, the significant variation across climate models regarding the future precipitation patterns represents a non negligible challenge for adaptation planning.

Weather-induced damages for road infrastructures are shown to be one of the biggest weather related cost for transport. This justifies focusing research on this area. Further selecting priority case studies about vulnerability and adaptation for that specific sector has been based on lessons learnt from the main studies conducted in e.g. US and in New Zealand. This is summarised as follows:

- Future trends of impacts associated with **heavy precipitations and floods**, especially scouring risk of river bridges: this effect is currently the main cause of bridge failure and could even be more important where rainfalls and floods will become more intense and frequent.

- Impacts associated with **higher temperatures** and heat stress:
    - road asphalt cracking,
    - rail track buckling.

- **Sea level rise and sea storms**: Land transport infrastructures in the coastal zone are likely to be exposed to greater risks from inundation and coastal erosion:
    - High waves and stormy conditions may wash away roads, disrupting access and requiring major repairs to restore road links. Potential for injury/death to road users exists.

- Coastal inundation and increased sea level rise may increase erosion of coastal structures, requiring more frequent inspection and repairs, and causing potential disruption.
- Increased saline intrusion at coastal bridges may lead to accelerated material deterioration.
- Some low lying airports could also be temporarily or permanently inundated transport and sea ports infrastructures progressively unavailable without adaptive retrofitting measures (e.g. raising decks, storage areas or causeways).

The selected priorities for detailed assessment in this project have been selected accordingly, also taking into account of available data and information. This is summarised in Table 11.

				Area for cost quantification			
Mode	**Transport system component**	**Typical infrastructure life**	**Chapter in this report**	**Asset at risk**	**Adaptation measure**		***Avoided impacts***
					autonomous	**Planned**	
road	infrastructure	7-10 years maintenance cycle	Chapter 4	Mapping future changing risk for road pavemet cracking	changing asphalt binder (*)	-	*- reduce road pavement degradation* *- avoid accidents (vehicle damages, injuries, fatalities)*
rail	infrastructure and operation	50-100 years track life	Chapter 5	Mapping future changing risk for rail buckling	speed limitations changing track conditions	-	*- reduce rail track buckling damage* *- avoid accidents (vehicle damages, injuries, fatalities)*
road rail	infrastructure (bridges)	> 100 yr life	Chapter 6	Mapping future risk for river bridge scour		- rip rap, - strenghtening of bridge foundations with concrete	*- damages to bridges due to scour* *- accidents, fatalities*
road	infrastructure	.> 100 yr life	Chapter 7	Value of infrastructure at risk of permanent or temporary inundation		-	-

(*) less stringent frost related risk mitigation measure also considered

Table 11: Selected impacts and adaptation measures considered for quantified assessment

For the sake of completeness, together with the adaptation of road asphalt, the impact of milder winter (frost effects) is also analysed in chapter 4.

4 Adaptation to higher temperatures: Road pavement

4.1 Heat stress and asphalt binder

4.1.1 Problem description

Adequate design and maintenance of road pavement for road network are essential for good transport servicing and road safety. The development of a wide variety of asphalts and asphalt binders has enabled to adjust road pavement characteristics to the local weather conditions. Depending on the climate conditions, weather constraints can consist into very cold winter conditions and frequent freeze-thawing cycles, intense precipitation and/or hot summer conditions. Weather constraints are in some cases particularly challenging for maintenance operators, if several of them are experienced over a year or even shorter period. For instance safety requirement implies specific road pavement and asphalt design in case of frequent intense rainfalls and frequent freezing days.

Road pavements also deteriorate as a result of traffic load together with weather conditions. Both temperature and precipitation represent weather stress parameters that can first contribute to initiate and accelerate some damaging effects. Such damaging effects are well known and intensively researched in the field of road engineering. Modelling tools, standard equations are developed in order to predict the different pavement defects (see for instance, the World Bank Highway Development Management tools - HDM-4[27]).

In Europe, although exact information is not readily available, the major portions of roads are paved. Unpaved roads are mainly found in remote areas that are exposed to weather conditions which would make their maintenance cost excessive (e.g. North Sweden, North Finland). Bituminous based pavement also dominates.

A general warming all over Europe is expected in the future, though with different levels of temperature increases could require modification in road pavement design and maintenance.

Hotter summer temperatures could imply changing asphalt properties. The type of asphalt and asphalt binder required to sustain certain temperature conditions are defined in current standards.

Upgrading asphalt performance to new – warmer - climate conditions is therefore one adaptation measure to be envisaged in the future in order to maintain road transport serviceability and safety. This may result in an increase of road maintenance cost. The next sections assess the future needs for such an adaptation measure in Europe and associated costs, successively describing the estimation method, the data situation regarding road network, and then presenting and discussing the cost estimates.

4.1.2 Methodology, data and assumptions

The EU standard EN13108 specifies the allowed mixtures for asphalt and their use. However available cost data for the different mixtures relate to United States. This cost analysis is following the approach recently implemented for US in a study contracted by EPA (Chinowski et al, 2011)[28]. This approach is based on existing guidelines for road pavement in US (Superpave)[10] as it can be assumed that similar guidelines are applied in Europe. The method is summarised as follows:

4.1.2.1 Climate data and indicator

The **7-day pavement temperature** is used as the climate related indicator to determine the level of adaptation of asphalt binder. It is defined as the of the highest daily pavement temperature for the 7 hottest consecutive days in a year[11].

The relation between pavement temperature and ambient temperature is assumed as:

$$Tp = 0.9545\ (Ta-0.00618\ L^2 + 0.2289\ L + 42.2)-17.78$$

Where Tp is the pavement temperature (˚C)
Ta is the ambient temperature (˚C)
L is the latitude (arc degrees)

Based on available maximum daily temperature, the average value for 7-day maximum ambient temperature is calculated for each 25 km * 25 km grid (or 50 km * 50 km, depending on the scenario) for each climate change scenario listed in section 3.3.1 and each time interval (1991-2010, 2041-2070, 2071-2100). This then allows deriving the corresponding gridded 7-day pavement temperature values.

4.1.2.2 Asphalt binder performance and cost

Performance asphalt grades prescribed in that country (Superpave)[29] and corresponding 7day-maximum pavement temperatures are given in next table. It also provides the cost per unit of lane. The last column has converted the original cost value from the US EPA study into €/km (1 €~1.3 USD).

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[10] Superpave: see http://www.il-asphalt.org/superpave.html

[11] The 7-day maximum temperature is calculated as follows: "For each day in a year, the average of maximum air temperature for each of the corresponding consecutive seven days is calculated. A marching forward in time takes place, i.e. the first day of the seven-day sequence is dropped and one day is added to the end to complete the set again, and the calculations are repeated. This way, a large number of average seven-day maximum air temperatures are obtained. The largest of all these averages for that particular year is selected as the 'Highest Averaged seven-day Daily Maximum Air Temperature'. The process is repeated for all the years for which temperature records are available. For example, if there are 30 years of record at one station, 30 values will be obtained for 7-day maximum temperature, one for each year. The mean value of these 30 numbers will be calculated, and converted into pavement temperature." (http://training.ce.washington.edu/wsdot/modules/03_materials/03-3_body.htm)

grade	Tmaxp_7day (ºC)	cost (USD/lane miles)	cost (€/km lane)
PG-46	46	197 000	94 182
PG-52	52	210 000	100 397
PG-58	58	225 000	107 568
PG-64	64	241 000	115 217
PG-70	70	258 000	123 345
PG-76	76	276 000	131 950
PG-82	82	295 000	141 034

Table 12: Performance grade

4.1.2.3 Road infrastructures

The adaptation cost to higher heat stress will depend on future climate conditions and on the future transport density network. It is assumed that the current transport network will not dramatically change until the end of the century, which is obviously a strong assumption especially by 2070-2100. It is however impossible to produce a realistic projection about its future feature. This information about current transport network is taken from the Transtools model[12].

The country level aggregated road length derived from Transtools model doesn't cover all transport network (main roads and highways only)[13]. For this reasons, costs estimates were adjusted accordingly.

4.1.2.4 Adaptation cost calculation

Cost associated with asphalt binder is calculated by multiplying the upper cost figures (Table 12) with the Transtools NUT3[14] level road length information (highways, national roads, secondary roads). Assuming an average number of lanes for each type of road, (respectively 5, 3 and 2), the costs at NUTS3 is calculated, aggregated at country level and adjusted to correct for the gap between Transtools network and official statistics.

4.1.3 Results

4.1.3.1 Exposure and vulnerability

The next figure shows the change in exposure for the three A1B scenarios, as expressed as the difference in 7-day maximum pavement temperature between period 2070-2100 and current period (1990-2010). Each scenario projects specific geographical pattern for changing temperature. Southern regions are, in all three cases expected to experience important temperature increase (larger than 3ºC to 4ºC). Such warming levels are also expected in other areas, but with inter-model variation. Scenario A1B-DMI even projects low changes for Middle / North Europe.

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[12] http://energy.jrc.ec.europa.eu/transtools/

[13] Transport statistical pocket 2011: bookhttp://ec.europa.eu/transport/publications/statistics/pocketbook-2011_en.htm

[14] NUTS stands for Nomenclature of Territorial Units for Statistics in Europe. NUTS3 is the smallest unit definition.

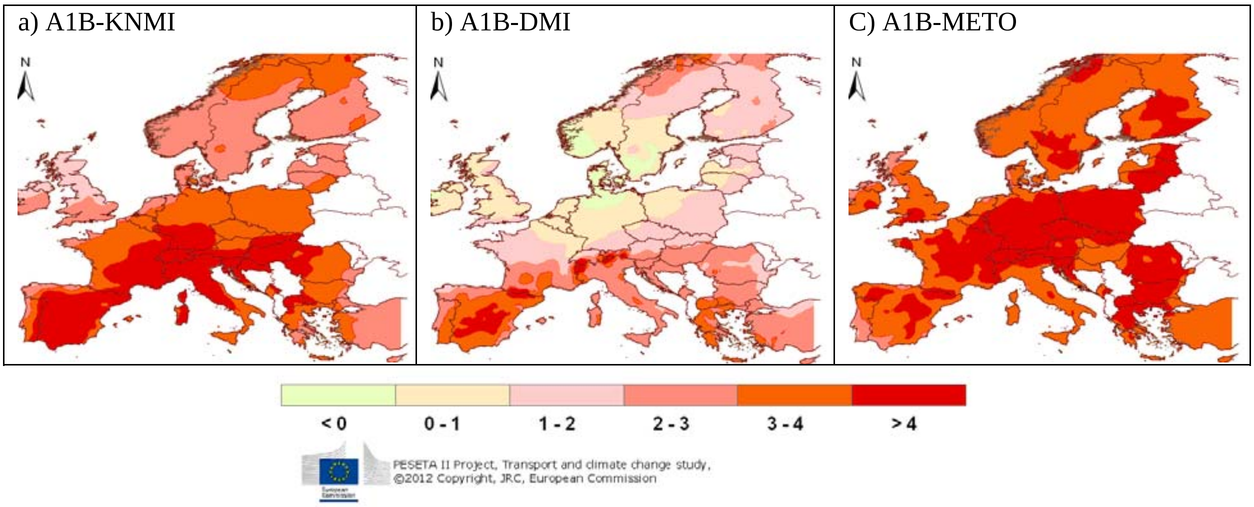

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**Figure 9: Change in 7-day maximum pavement temperature in the different climate zones in Europe in the case of the A1B scenarios
(period 2070-2040 compared with 1990-2010)**

4.1.3.2 Cost of adaptation

Next two tables provide the country level annual costs to upgrade asphalt binder for the different scenarios, respectively for the periods 2040-2070 and 2070-2100 and for the E1, A1B and RCP8.5 scenarios. In total, for the A1B scenario, the additional cost for EU27 would be in a range of 38.5 – 135 million €/yr by 2040-2070 and 65-210 million €/year by 2070-2100. Expressed in percentage of current road maintenance costs (~26 billion €/year), this represents respectively from 0.1% to 0.5% and 0.2%-0.8% (0.4% and 0.6% mean costs respectively).

	Additional cost in 2040-2070 (million €)/yr								
	E1				**A1B**				**RCP8.5**
	MPI-E1-r1	MPI-E1-r2	MPI-E1-r3	**average**	A1B-KNMI	A1B-DMI	A1B-METO	**average**	
AT	1.89	0.84	0.44	1.06	2.08	2.00	2.22	2.10	2.16
BE	4.91	5.25	2.20	4.12	9.07	0.08	14.42	7.86	8.69
BG	7.42	0.78	1.32	3.18	6.37	4.39	6.25	5.67	6.25
CZ	3.65	1.78	0.90	2.11	5.87	2.74	3.59	4.06	4.07
DE	16.77	10.43	5.91	11.04	27.65	7.02	23.62	19.43	19.18
DK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ES	24.34	1.03	1.76	9.04	6.37	4.84	8.13	6.45	7.85
FI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FR	22.72	2.28	2.24	9.08	8.32	4.10	11.29	7.90	8.31
GR	0.62	0.10	0.12	0.28	0.24	0.42	0.95	0.54	0.63
HU	10.54	2.20	1.86	4.87	3.36	0.00	25.40	9.58	9.68
IE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IT	5.61	1.85	2.56	3.34	9.46	6.73	8.92	8.37	10.14
LT	1.35	0.59	0.39	0.78	0.00	0.00	4.90	1.63	1.07
LU	0.04	0.02	0.01	0.03	0.05	0.02	0.05	0.04	0.04
LV	0.02	0.01	0.01	0.01	0.00	0.00	0.09	0.03	0.02
NL	7.18	3.22	1.25	3.89	4.56	0.00	7.98	4.18	4.98
PL	4.62	2.46	1.53	2.87	13.36	0.98	4.60	6.31	5.66
PT	3.46	0.19	0.52	1.39	2.47	1.92	3.00	2.46	3.05
RO	1.29	0.27	0.26	0.61	1.65	1.13	1.62	1.47	1.55
SE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SI	4.67	0.74	0.76	2.06	1.58	1.26	3.53	2.12	2.27
SK	2.06	0.50	0.31	0.96	1.21	0.81	2.83	1.62	1.18
UK	0.41	0.61	0.17	0.40	0.00	0.00	1.84	0.61	0.35
EU	**123.58**	**35.15**	**24.53**	**61.09**	**103.66**	**38.45**	**135.24**	**92.45**	**97.12**

Table 13: Adaptation Cost estimate for the three groups of scenarios A1B, E1 and RCP8.5 and their average at national level (period 2040-2070)

	Additional cost in 2070-2100 (million €)/yr								
	E1				**A1B**				**RCP8.5**
	MPI-E1-r1	MPI-E1-r2	MPI-E1-r3	**average**	A1B-KNMI	A1B-DMI	A1B-METO	**average**	
AT	3.10	1.00	0.73	1.61	3.77	3.46	5.35	4.19	5.93
BE	8.60	4.25	3.51	5.46	15.60	0.44	15.70	10.58	20.27
BG	8.74	1.21	1.40	3.79	10.25	5.52	9.03	8.27	11.43
CZ	2.67	0.11	0.14	0.97	7.71	4.51	5.56	5.93	3.88
DE	24.88	8.11	5.06	12.68	37.53	9.82	39.33	28.89	45.77
DK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EE	0.40	0.20	0.22	0.27	0.00	0.00	0.84	0.28	0.65
ES	34.33	2.95	16.08	17.79	14.55	9.54	11.54	11.88	33.27
FI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FR	23.25	3.37	12.21	12.95	17.87	6.94	17.63	14.14	24.98
GR	1.61	0.48	0.63	0.91	0.89	0.94	1.85	1.23	3.48
HU	16.82	2.61	2.63	7.35	27.33	0.40	30.01	19.25	21.13
IE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IT	5.32	15.85	9.82	10.33	11.95	9.01	9.70	10.22	90.68
LT	2.26	0.44	0.58	1.09	0.61	0.00	9.11	3.24	3.17
LU	0.04	0.01	0.01	0.02	0.07	0.02	0.05	0.05	0.07
LV	0.66	0.33	0.29	0.43	0.00	0.00	3.14	1.05	1.72
NL	8.90	1.07	3.52	4.50	9.23	0.00	12.26	7.16	12.46
PL	9.89	4.98	4.01	6.29	17.36	6.69	7.73	10.59	23.28
PT	5.39	1.44	1.36	2.73	4.36	3.64	3.66	3.88	8.87
RO	1.53	0.08	0.30	0.64	2.65	1.43	2.34	2.14	2.57
SE	0.67	0.11	0.10	0.29	0.00	0.00	4.33	1.44	0.90
SI	5.36	1.99	3.78	3.71	4.88	1.26	5.33	3.83	9.89
SK	3.65	1.10	1.21	1.99	4.15	1.30	5.15	3.53	5.69
UK	2.12	0.58	0.38	1.03	1.85	0.00	10.02	3.96	3.51
EU	**170.19**	**52.28**	**67.99**	**96.82**	**192.61**	**64.93**	**209.65**	**155.73**	**333.61**

Table 14: Adaptation Cost estimate for the three groups of scenarios A1B, E1 and RCP8.5 and their average at national level and per climate zone (period 2070-2100)

For the two periods, on the average, the E1 scenarios show lower costs, but it is to be noted that the first realisation scenario (MPI-E1-r1) results in costs even larger than the average costs for A1B scenarios. The estimated average costs for the period 2040-2070 for the RCP8.5 scenario do not dramatically differ from the A1B scenarios.

Additional RCP8.5 driven scenarios would be needed to better assess the range of potential costs, taking into account the uncertainty associated with model climate sensitivity and regional downscaling.

4.2 Consequences of milder winter conditions

Frost effects on road pavement represent the most important source of deterioration in regions experiencing cold winter conditions. Two main effects are deep or moderate frost depth and freeze-thaw cycles (FTC). The effects are also influenced by precipitation conditions. Besides weather parameters, traffic is also a major factor to be considered. The assessment of this problem is therefore a multivariate problem and it is out of the scope of this project to perform a detailed analysis for all Europe.

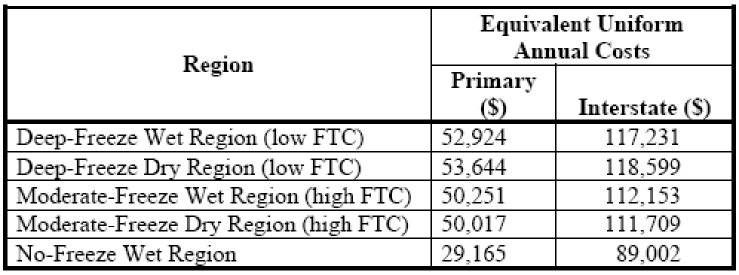
Instead, in view of drawing indicative future costs associated with these effects this analysis bases upon a detailed statistical analysis reported in an exhaustive report by the US Federal Highway Administration (FHWA, 2006)[30]. In that analysis, a broad statistical analysis has been performed in US, considering a wide set of explanatory variables[15]. The correlation between Freeze-thaw cycles frequency and Freezing Day index was analysed and six main regions were defined, characterized by their degree of freezing conditions and multiple freeze-thaw cycle. It was shown that the severity of deterioration effects associated with frost (frost depth, multiple freeze-thaw cycles) could grouped into those six main weather types as described in Table 14.

	FDI	**average precipitation (mm/yr)**
Deep-Freeze Wet (low FTC)	>400	>500
Deep-Freeze Dry (low FTC)		<500
Moderate-Freeze Wet (high FTC)	50-400	>500
Moderate-Freeze Dry (high FTC)		<500
No-Freeze wet	<50	>500

Table 15: Characterization of cold weather conditions for road pavement (source: FHWA)

Prediction models for the different deteriorations (roughness, rutting, and distress) were then developed. A life cycle cost assessment (LCCA) was then performed to evaluate pavement costs in the various climate settings. Annualized costs for both interstate and normal highways were calculated, under both a deterministic and a probabilistic LCCA.

Table 16 shows the estimated costs for the two types of highways.



Region	**Equivalent Uniform Annual Costs**	
	Primary ($)	**Interstate ($)**
Deep-Freeze Wet Region (low FTC)	52,924	117,231
Deep-Freeze Dry Region (low FTC)	53,644	118,599
Moderate-Freeze Wet Region (high FTC)	50,251	112,153
Moderate-Freeze Dry Region (high FTC)	50,017	111,709
No-Freeze Wet Region	29,165	89,002

Table 16: Deterministic LCCA for highways (source: FHWA, 2006)

These costs figures were used in this research project to produce a first order estimate of the changes in costs associated with winter conditions for Europe. Based on the different climate scenario data, the freezing-day index and annual precipitations were derived at grid level (25 x 25 km or 50 x 50 km) so that each of them could be assigned to one of the six weather climates. The corresponding average annual life cycle cost (between interstate and normal highway) were used (assuming a 1.3 conversion rate between USD and €) to derive the average LCCA cost at grid level, and then at country level, for each time interval. The multiplication by highway length

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[15] Pavement Structure Categorical, Freezing Index (FI), Freeze-Thaw Cycles, Cooling Index, Annual Precipitation, Pavement Age, Subgrade Type, Base Type, Asphalt Cement Concrete Thickness, Slab Thickness, Traffic Loading/Structural Capacity Ration

(TELEATLAS) then results in an aggregated cost estimate. The estimated costs are provided in Table 17 and Table 18 for the two time intervals.

A systematic reduction in costs is for all countries. The A1B and RCP8.5 show the largest decreases. Overall, this would result in reducing the annual maintenance cost by 0.4% to 2.4%.

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	Additional cost in 2040-2070 (million €)/yr								
	E1				**A1B**				**RCP8.5**
	MPI-E1-r1	MPI-E1-r2	MPI-E1-r3	**average**	A1B-KNMI	A1B-DMI	A1B-METO	**average**	
AT	-0.4	-0.4	-0.6	-0.5	-0.5	-0.3	-1.3	-0.7	-0.7
BE	-5.6	-4.9	-7.7	-6.1	-4.3	-3.1	-19.0	-8.8	-9.1
BG	-3.3	-1.5	-3.6	-2.8	-2.9	-1.7	-8.4	-4.3	-4.5
CZ	0.0	0.0	0.0	0.0	-0.1	0.0	0.0	0.0	0.0
DE	-12.4	-10.4	-15.2	-12.7	-0.2	0.2	-48.3	-16.1	-16.8
DK	-4.4	-3.6	-5.2	-4.4	0.0	0.0	-14.8	-4.9	-5.2
EE	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1	-0.1	-0.1
ES	-39.9	-52.7	-57.2	-49.9	-66.6	-64.6	-78.3	-69.9	-74.0
FI	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	-0.2	-0.1	-0.1
FR	-17.3	-20.3	-24.0	-20.5	-24.6	-15.1	-53.5	-31.1	-30.8
GR	-4.7	-2.9	-5.0	-4.2	-2.1	-3.6	-13.2	-6.3	-6.1
HU	-0.1	-0.1	-0.1	-0.1	0.0	0.1	-0.5	-0.2	-0.2
IE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IT	-10.5	-9.8	-12.5	-10.9	-12.0	-15.1	-15.7	-14.3	-14.9
LT	-0.3	-0.3	-0.4	-0.3	-0.2	-0.1	-0.9	-0.4	-0.4
LU	-0.1	-0.1	-0.2	-0.1	0.0	0.0	-0.6	-0.2	-0.2
LV	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	-0.3	-0.2	-0.2
NL	-12.0	-8.1	-14.8	-11.7	-1.6	-1.6	-41.7	-15.0	-15.4
PL	-0.4	-0.3	-0.4	-0.3	-0.4	-0.4	-0.4	-0.4	-0.5
PT	5.1	-12.0	-14.9	-7.3	-16.9	-11.3	-18.5	-15.6	-15.8
RO	-0.2	-0.2	-0.3	-0.2	-0.1	0.0	-0.9	-0.3	-0.3
SE	-0.9	-0.7	-1.0	-0.9	-0.7	-0.9	-1.6	-1.0	-1.2
SI	-0.2	-0.2	-0.3	-0.2	0.0	0.0	-1.0	-0.3	-0.4
SK	-0.1	-0.1	-0.2	-0.2	-0.2	-0.1	-0.3	-0.2	-0.2
UK	-1.7	-1.3	-2.0	-1.7	-2.1	-2.2	-2.6	-2.3	-2.4
EU27	**-109.7**	**-130.1**	**-165.9**	**-135.2**	**-135.6**	**-119.8**	**-324.0**	**-193.1**	**-199.5**

Table 17: Reduction of annual costs associated with winter conditions and road pavement for the three groups of scenarios A1B, E1 and RCP8.5 and their average at national level and per climate zone (period 2040-2070)

	Additional cost in 2070-2100 (million €)/yr								
	E1				**A1B**				**RCP8.5**
	MPI-E1-r1	MPI-E1-r2	MPI-E1-r3	**average**	A1B-KNMI	A1B-DMI	A1B-METO	**average**	
AT	-2.5	-2.5	-3.3	-2.8	-0.7	-0.7	-10.3	-3.9	-4.1
BE	-11.5	-10.1	-15.7	-12.4	-16.5	-15.9	-21.4	-18.0	-18.6
BG	-5.8	-2.6	-6.4	-4.9	-6.4	-5.8	-10.8	-7.6	-8.0
CZ	-0.7	-0.6	-0.9	-0.8	0.0	0.0	-2.9	-1.0	-1.0
DE	-63.6	-53.6	-78.0	-65.1	-7.7	-14.3	-226.1	-82.7	-86.4
DK	-11.0	-9.0	-13.1	-11.0	-1.6	-8.0	-27.7	-12.4	-13.1
EE	-0.2	-0.1	-0.2	-0.2	-0.1	-0.1	-0.3	-0.2	-0.2
ES	-53.0	-70.1	-76.1	-66.4	-142.3	-64.7	-71.8	-93.0	-98.4
FI	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.3	-0.2	-0.2
FR	-35.1	-41.3	-48.7	-41.7	-67.0	-49.0	-73.5	-63.2	-62.7
GR	-9.8	-6.0	-10.5	-8.8	-13.1	-15.1	-11.1	-13.1	-12.7
HU	-12.5	-9.9	-15.4	-12.6	-0.1	0.0	-49.3	-16.4	-17.9
IE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IT	-18.3	-17.1	-21.7	-19.0	-24.1	-25.2	-25.2	-24.8	-25.8
LT	-0.7	-0.6	-0.9	-0.7	-0.8	-0.8	-0.9	-0.8	-0.9
LU	-0.5	-0.5	-0.7	-0.6	0.0	0.0	-2.5	-0.8	-0.9
LV	-0.2	-0.2	-0.3	-0.2	-0.3	-0.2	-0.3	-0.3	-0.3
NL	-27.0	-18.2	-33.3	-26.2	-26.0	-33.1	-41.7	-33.6	-34.5
PL	-0.4	-0.3	-0.4	-0.4	-0.1	-0.3	-0.9	-0.4	-0.5
PT	4.1	-9.7	-12.1	-5.9	-12.9	-8.9	-16.1	-12.6	-12.8
RO	-1.0	-0.7	-1.2	-1.0	-0.2	-0.1	-3.6	-1.3	-1.4
SE	-1.5	-1.2	-1.7	-1.5	-0.5	-0.8	-4.2	-1.8	-2.1
SI	-0.8	-0.8	-1.1	-0.9	-0.7	-0.3	-3.0	-1.4	-1.4
SK	-1.6	-1.3	-2.0	-1.6	-0.2	-0.2	-5.7	-2.0	-2.2
UK	-6.2	-4.7	-7.4	-6.1	-6.1	-6.0	-13.7	-8.6	-9.1
EU27	**-260.1**	**-261.3**	**-351.3**	**-290.9**	**-329.3**	**-253.4**	**-624.4**	**-402.4**	**-415.4**

Table 18: Reduction of annual costs associated with winter conditions and road pavement for the three groups of scenarios A1B, E1 and RCP8.5 and their average at national level and per climate zone (period 2070-2100)

4.2.1 Total costs

The sum of costs changes associated with future heat stress and winter conditions are given in Table 19 and Table 20 for the two future periods. Overall, the net costs are negative (-74 to -102 million € for the first period and -247 to -82 million € for the second period). It is to be noted that for both periods, the cost variation for one same emission scenario (E1 and A1B respectively) is very large. For the second period, the A1B scenario shows the highest cost reduction, followed by E1 and then RCP8.5 (-82 million €/year). Some countries could incur slightly positive costs (e.g. Italy, Poland).

The respective contributions of heat stress and winter conditions are displayed in Figure 10 for EU27 and for the different scenarios.

	Additional cost in 2040-2070 (million €)/yr								
	E1				**A1B**				**RCP8.5**
	MPI-E1-r1	MPI-E1-r2	MPI-E1-r3	**average**	A1B-KNMI	A1B-DMI	A1B-METO	**average**	
AT	1.5	0.4	-0.1	0.6	1.6	1.7	1.0	1.4	1.4
BE	-0.7	0.3	-5.5	-1.9	4.8	-3.0	-4.6	-0.9	-0.4
BG	4.2	-0.7	-2.3	0.4	3.5	2.7	-2.1	1.4	1.7
CZ	3.6	1.8	0.9	2.1	5.8	2.7	3.6	4.0	4.0
DE	4.4	0.0	-9.3	-1.6	27.4	7.2	-24.7	3.3	2.4
DK	-4.4	-3.6	-5.2	-4.4	0.0	0.0	-14.8	-4.9	-5.2
EE	0.0	0.0	-0.1	0.0	0.0	0.0	-0.1	-0.1	-0.1
ES	-15.5	-51.7	-55.5	-40.9	-60.2	-59.8	-70.2	-63.4	-66.1
FI	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	-0.2	-0.1	-0.1
FR	5.4	-18.0	-21.7	-11.4	-16.3	-11.0	-42.2	-23.2	-22.5
GR	-4.1	-2.8	-4.9	-3.9	-1.8	-3.1	-12.3	-5.7	-5.5
HU	10.4	2.1	1.7	4.8	3.3	0.1	24.9	9.4	9.5
IE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IT	-4.9	-8.0	-9.9	-7.6	-2.6	-8.3	-6.8	-5.9	-4.7
LT	1.0	0.3	0.0	0.4	-0.2	-0.1	4.0	1.2	0.6
LU	-0.1	-0.1	-0.2	-0.1	0.0	0.0	-0.6	-0.2	-0.2
LV	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1	-0.2	-0.1	-0.2
NL	-4.8	-4.9	-13.6	-7.8	3.0	-1.6	-33.7	-10.8	-10.4
PL	4.3	2.2	1.1	2.5	13.0	0.6	4.2	5.9	5.2
PT	8.5	-11.8	-14.4	-5.9	-14.4	-9.4	-15.5	-13.1	-12.8
RO	1.0	0.1	0.0	0.4	1.6	1.1	0.8	1.1	1.2
SE	-0.9	-0.7	-1.0	-0.9	-0.7	-0.9	-1.6	-1.0	-1.2
SI	4.5	0.5	0.5	1.8	1.6	1.3	2.5	1.8	1.9
SK	1.9	0.4	0.1	0.8	1.0	0.7	2.6	1.4	1.0
UK	-1.3	-0.7	-1.8	-1.3	-2.1	-2.2	-0.8	-1.7	-2.1
EU27	**13.9**	**-94.9**	**-141.4**	**-74.2**	**-32.0**	**-81.4**	**-188.7**	**-100.7**	**-102.4**

Table 19: Total cost changes associated with heat stress and winter conditions and road pavement for the three groups of scenarios A1B, E1 and RCP8.5 and their average at national level and per climate zone (period 2040-2070)

	Additional cost in 2070-2100 (million €)/yr								
	E1				**A1B**				**RCP8.5**
	MPI-E1-r1	MPI-E1-r2	MPI-E1-r3	**average**	A1B-KNMI	A1B-DMI	A1B-METO	**average**	
AT	0.6	-1.5	-2.5	-1.1	3.1	2.8	-5.0	0.3	1.8
BE	-2.9	-5.8	-12.2	-7.0	-0.9	-15.5	-5.7	-7.4	1.6
BG	3.0	-1.4	-5.0	-1.1	3.8	-0.2	-1.7	0.6	3.4
CZ	1.9	-0.5	-0.8	0.2	7.7	4.5	2.7	5.0	2.9
DE	-38.7	-45.5	-72.9	-52.4	29.8	-4.5	-186.8	-53.8	-40.6
DK	-11.0	-9.0	-13.1	-11.0	-1.6	-8.0	-27.7	-12.4	-13.1
EE	0.2	0.0	0.0	0.1	-0.1	-0.1	0.5	0.1	0.4
ES	-18.7	-67.2	-60.1	-48.7	-127.8	-55.2	-60.3	-81.1	-65.2
FI	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.3	-0.2	-0.2
FR	-11.9	-37.9	-36.5	-28.8	-49.2	-42.0	-55.9	-49.0	-37.7
GR	-8.2	-5.5	-9.8	-7.9	-12.2	-14.2	-9.3	-11.9	-9.3
HU	4.3	-7.3	-12.8	-5.3	27.3	0.4	-19.2	2.8	3.3
IE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IT	-12.9	-1.3	-11.9	-8.7	-12.1	-16.2	-15.5	-14.6	64.8
LT	1.5	-0.1	-0.3	0.4	-0.2	-0.8	8.2	2.4	2.2
LU	-0.5	-0.5	-0.7	-0.6	0.1	0.0	-2.5	-0.8	-0.8
LV	0.4	0.1	0.0	0.2	-0.3	-0.2	2.8	0.8	1.4
NL	-18.1	-17.2	-29.8	-21.7	-16.7	-33.1	-29.5	-26.4	-22.0
PL	9.5	4.7	3.6	5.9	17.3	6.4	6.8	10.2	22.8
PT	9.5	-8.2	-10.7	-3.2	-8.5	-5.2	-12.5	-8.7	-3.9
RO	0.5	-0.6	-0.9	-0.3	2.4	1.3	-1.2	0.8	1.2
SE	-0.8	-1.1	-1.6	-1.2	-0.5	-0.8	0.1	-0.4	-1.2
SI	4.5	1.2	2.6	2.8	4.2	0.9	2.3	2.5	8.5
SK	2.1	-0.2	-0.8	0.4	4.0	1.1	-0.6	1.5	3.5
UK	-4.1	-4.2	-7.0	-5.1	-4.2	-6.0	-3.7	-4.7	-5.6
EU27	**-89.9**	**-209.0**	**-283.3**	**-194.1**	**-136.7**	**-188.4**	**-414.8**	**-246.6**	**-81.8**

Table 20: Total cost changes associated with heat stress and winter conditions and road pavement for the three groups of scenarios A1B, E1 and RCP8.5 and their average at national level and per climate zone (period 2070-2100)

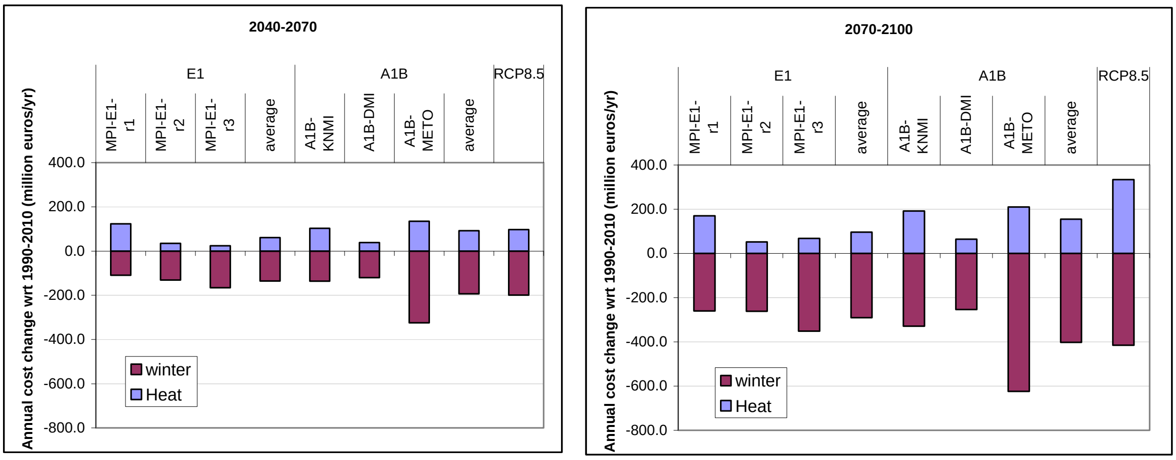

Figure 10: Comparison of EU-wide costs changes associated with heat stress and winter conditions for road pavement

4.3 Concluding remarks

Changes in road pavement design and maintenance are to be expected in the future as a result of changing temperature profiles. Overall, milder winter conditions are expected to require less costly materials and maintenance operations and will therefore reduce spending for highways owners (0.4% to 2.5% of current maintenance costs for EU27, depending on the scenario). The analysis didn't assess the changes which could be expected in a nearer future, especially some possible transitional increases in multiple freeze-thawing cycle effects in some parts of Europe. In that case, maintenance and repairing operations could represent a cost increase compared to today.

Road Asphalt binder adaptation to future climate warming is a measure already feasible. The EU27-wide costs for that measure by 2040-2070 estimated to 35-135 million €/yr over the different climate scenarios considered, representing 0.1% to 0.5% of current road maintenance costs. In the longer term, these costs could be or the order of 1% to 1.2% of current maintenance cost in the A1B and RCP8.5 scenario. On the average, under a 2ºC scenario (E1), the costs would be maintained to their earlier level.

These costs are overall suggested to be moderate and outweighed by the negative costs expected from milder winter conditions. Also, one peculiar aspect of that measure is the involved short life (~7 year for asphalt renewal), which enables an iterative adjustment of asphalt characteristics according to future improved climate projections and continuous technique improvements.

The significant inter-model variation of assessed costs shows the need to consider scenario ensembles for adaptation measure analysis.

5 Adaptation to heat stress: Rail track buckling effect

5.1 Problem description

Depending on ambient temperature, rail track can be subject to contraction (under cold temperature) or dilatation (hot temperature) forces. Continuous welded rail (CWR) that has being generalised over the last 30 years all over Europe and in many parts of the world is particularly subject to these effects which can result in track breaks in winter season or track deformation in summer season. For this reason CWR requires special track anchoring and maintenance measures.

Climate change will result in higher average temperature and more frequent extreme high temperatures, which can potentially enhance the risk of rail track deformation effect and rail track buckling. "Rail Track buckling" is defined as the formation of large lateral misalignments in continuous welded rail track (CWR). This problem which can result in catastrophic derailments has been subjected to intense and continuous engineering research over the last 20 years. Speed limitation restriction, as guided by temperature forecast is the most common preventive measure.

In US, statistics over the period 1998-2002 indicate an average of 38 derailments a year with an increasing yearly damage level as high as $17 million in 2002 (Volpe National Transportation Systems) [31]. No such statistics were found for Europe.

CWR is currently the most common practice in Europe. Rail track proneness to buckling is influenced by factors such as sleeper type, rail weight, fastening type, radius, ballast profile and singularities (Laurans, 2012)[32]. Buckling risk is higher in case of wooden sleepers than concrete sleepers.

The Track buckling research paper from the Volpe National Transportation Systems[16] provides a good summarised description of the problem and underlying factors:

> "*Both curved and tangent tracks are susceptible to buckling with typical curve buckle amplitudes ranging from 6"-14" and tangent buckles from 12"-28".*
>
> *Buckles are typically caused by a combination of* ***three major factors****:*
> - *high compressive forces,*
> - *weakened track conditions,*
> - *and vehicle loads (train dynamics).*
>
> ***Compressive forces*** *result from stresses induced in a constrained rail by temperature above its "****stress free****" state, and from mechanical sources such as braking, rolling friction and wheel flanging on curves. The temperature of the rail at the "stress-free" state is known as the rail neutral temperature (i.e. the temperature at which the rail experiences zero longitudinal force). Initially, the rail's installation temperature or "anchoring temperature" is the* ***rail's neutral temperature*** *(NDLR: also called "****stress free temperature****" – denoted* ***SFT****). Hence, at rail temperatures above the neutral, compressive forces are generated, and at temperatures below the neutral, tensile forces are developed.*
>
> *Track maintenance practices address the* ***high thermal load problem*** *by anchoring the rail at (neutral) temperature of 95 -110 °F (NDLR: 35°C – 43°C temperature on track[17]). This high neutral temperature*

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[16] Track buckling research, http://www.volpe.dot.gov/coi/pis/work/archive/docs/buckling.pdf

range prevents the generation of excessively high buckling forces even when the rail temperatures reach 130 -150 °F (NDLR: 54ºC – 65ºC temperature on track[18]).

***Weakened track conditions** impacting the tracks buckling potential include:*

1. *reduced track resistance,*
2. *lateral alignment defects, and*
3. *lowered rail neutral temperature.*

Track resistance is the ability of the ballast, ties and fasteners to provide lateral and longitudinal strength to maintain track stability. Resistance is lowered if ballast is missing from under the ties, in the crib or from the shoulder. A full ballast section is important, especially on curves. Adequate ballast in the high side in curves should be on the order of 12"-18" to provide adequate lateral strength. Ballast on the low side is important because inward (pulling-in) movement in cold weather could lead to line defects and lowering of neutral temperature which could lead to a buckle when higher temperature rises occur in early spring. Track resistance is also lowered when ballast is disturbed. Surfacing, tie renewal and undercutting operations will weaken ballast resistance by as much as 40%-60% of undisturbed track. It is a usual industry practice to ***restrict train speed*** *to minimize train forces while ballast strength is being restored either by traffic or by mechanical consolidation means. Longitudinal resistance offered to the rail/tie structure by adequate rail anchoring is important to prevent rail running and hence the decrease of rail neutral temperature.*

Lateral alignment defects also reduce the track's buckling strength because buckles tend to initiate at alignment deviations. The larger the line defect, the more buckling prone the track will be. Alignment errors must be corrected in hot weather and in early spring when curves tend to realign themselves from a winter "pull-in" condition. Buckles can also initiate at bad, crooked welds.

Maintaining a stable and high rail neutral temperature is critical for buckling prevention. Neutral or force-free temperature of CWR is usually different from initial installation or anchoring temperature. This difference is attributed to several factors, including:

- *rail longitudinal movement: Rail longitudinal movement (creep) is due to train braking and traction forces, or to differential thermal forces (sun and shade).*
- *track lateral shift/radial breathing in curves, Track lateral shift can be caused by excessive truck hunting, and by lateral forces generated by curving or by lateral misalignments. Compressive and tensile forces can cause radial breathing of curves especially in weak ballast conditions.*
- *track vertical settlement which can occur on new or recently surfaced track, or in areas of weak subgrade conditions.*
- *maintenance activities that can influence neutral temperature changes including: lifting, lining, and tamping, replacing broken rail, de-stressing, and installing CWR in cold weather. Research to date has shown that typical CWR rail installation (stress-free) temperatures of 100°F (38ºC) can reduce in service to 50 - 60°F (10ºC - 15ºC) due to these effects.*

***Vehicle loads:** Track buckles usually initiate at small alignment deviations. Wheel loads and train action (dynamic uplift wave) tend to increase its size to levels which trigger the buckling process.*

Most buckling derailments tend occur deep in a train. Vehicles contribute to buckling by exerting lateral wheel forces in a curve. Lateral forces can also occur in tangent track from car movement caused by line or surface deviations or track hunting. The track must absorb this energy. Slack action, heavy dynamic braking and emergency brake applications can trigger a buckle. It is important to inspect track after a train passage in hot weather, especially if the track has recently been disturbed.

(Volpe National Transportation Systems)[19]

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[17] As a first approximation, corresponding ambient temperature are given by 2/3 T on track, thus 23ºC – 29ºC

[18] 36ºC – 43ºC ambient temperature

[19] Track buckling research, http://www.volpe.dot.gov/coi/pis/work/archive/docs/buckling.pdf

5.2 Rail track temperature and ambient temperature

Rail track temperature is depending on the ambient temperature and other factors such as solar radiation, humidity and wind intensity. Detailed correlations investigated in France (Girardi et al, 2011)[33] and in Australia (Munro, 2009)[34] have shown that both temperature and solar radiation are the two key explanatory factors. Good correlation between rail track temperature and these factors are aimed at in order to improve reliability of prediction for rail buckling risk and appropriate preventive measures. Unfortunately, the regression functions reported by such studies are region specific and can't be generalised over all Europe. Therefore, for this analysis a simplified correlation T_{track} ~3/4 Ta (Dobney, 2010)[36] is assumed.

5.3 Current practices to reduce derailment risk

Preventive measures to reduce rail buckling derailment risk include:

- Improving weather forecast and predictive capacity for rail track temperature
- Maintaining stress free temperature to its initial level
- Applying speed limits during high temperature spells.

5.3.1 Stress free Temperature

There is no EU standard regarding SFT setting rules. Applied stress free temperatures found in the reviewed literature and contacted experts for several countries in Europe are summarised in Table 21.

country	Stress Free Temperature (degrees C)	*source*
DE	23	*Ryan and Hunt*
ES	27	*Dobney*
FR	25	*Girardi*
IE	23	*Ryan and Hunt*
NL	25	*Ryan and Hunt*
UK	27	*Dobney*

Table 21: SFT values found in literature and through contacted experts
Sources: Ryan and Hunt (2008)[35], Dobney (2010)[36], Giradi (2011)[37]

Next indications are also of interest:

- SFT should be set to balance the risk of rail buckling at high temperatures and rail cracking at low temperatures (Dobney, 2010)
- Since the track is more stable when the rail is in tension at temperatures below the neutral temperature, the target neutral temperature is generally 75 percent of the expected maximum temperature of the region (US Climate Change Programme, 2008)[38]. In the following, we will refer to this rule to as the "¾ T_{max}" rule. This standard rule was however not confirmed by some experts consulted during this analysis.

- Same SFT are usually used across the entire country network (Ryan and Hunt)[35]. Deviation from the country values, together with local maintenance and work rules, can however be envisaged in special cases (e.g. France).

5.3.2 Speed limitations

A derailment can occur when a buckled section of track is not detected on time. In order to prevent this railroads issue blanket slow orders.

In Australia, a 90 km/h speed restriction is applied on specific lines between 12:00 and 20:00 on days where the temperature is forecast to reach or exceed 36ºC (~54ºC rail track temperature).
Next table shows the safety margins (above SFT) above which speed limits are assumed to be applied as reported by Dobney et al (2009)[39] and based on US research (Volpe)[31]. Accordingly, Critical Rail tracks Temperatures (CRT) are defined for the cases of good and inadequate ballast conditions.

The two sets of margins show the high influence of ballast conditions on rail buckling risk. In the case of "good ballast conditions", safety margins are large and, in the majority of cases, rail buckling risk is negligible. In the case of "inadequate ballast" speed limitation are applied as soon as SFT are exceeded by 13ºC. Unfortunately a clear definition for qualifying the ballast condition (good versus inadequate) was not found, making distinction and track characterisation at EU level difficult (Chapman, 2012)[40]. In the following, CRT70 and CRT30 will be used to denote the critical temperatures above which 70 km/h (45 to 90 km/h) and 30 km/h speed restriction should be applied.

	CRT - SFT (degree C)		
	on standby	impose speed reduction 45/90 km/h	impose speed restriction 30 km/h
Good condition	32	37	42
Inadequate ballast	10	13	15

Table 22: Margin values between CRT and SFT (track temperature)

It is to be noted that these safety margins do not perfectly reflect current practices all over Europe. In France for instance, nominal track may suffer rail temperatures up to 60°C. Non conform areas or track works areas are dealt with procedures: speed restrictions or survey depending on **real** rail temperature (Laurans, 2012).

While speed restrictions are effective to reduce rail derailment risks, this results in longer transit times, higher operating costs, shipment delays, reduced track capacity, and increased equipment cycle time leading to larger fleet sizes and costs. Reduced train speeds similarly affect passenger rail schedules, causing delays in travel schedules. (US Climate Change Programme, 2008)[38].

Statistics for Europe about rail buckling related speed limitations were not found. In New Zealand (Gardiner et al, 2009)[41], "*Rail heat stress and track buckling is mainly a summer phenomenon with about **quarter of the 4160 km** of track currently subject to heat speed restrictions*." This suggests significant consequences for rail transport performance. In Australia, the reported annual delays associated with rail track buckling prevention (Munro, 2009)[34] for the financial year 2007-2008 in the Victoria region ranges between 8 and 55 days depending on the region, representing 1170 – 4985 delays minutes. In total this represents a cost of 1.877 million AUD (~1.485 million €).

It is to be noted that the higher temperature on its own doesn't statistically determine the rail buckling risk. Important factor is also the difference between higher and lower rail temperature. The inter-seasonal maintenance (e.g. ballast surfacing, track cutting after winter) may represent a significant risk factor in colder countries.

5.4 Adaptation measures

Different types of measures to reduce buckling risk include:

- Improving prediction and monitoring of track temperature conditions: measurement of temperature is the most expensive although emerging technologies could improve the cost effectiveness (Munro, 2009). Prediction measures are cheaper than monitoring. Research efforts as those from Girardi (2011) contribute to improving their reliability.
- Use of new materials features (e.g. sleepers) and setting techniques (e.g. fasteners)
- Improved maintenance practices in order to maintain the stress free temperature and inter-seasonal repairing track and ballast resurfacing. Maintenance periods can also be adapted to local weather conditions. In France, maintenance season is a period of the year depending on the location, beginning between the 15th of May (south of France) and the 11th of June (north of France), finishing between the 3rd (north of France) and the 15th of September (south of France) (Laurans, 2012).
- Changing stress free temperature to adapt to new local conditions. The feasibility of such a new stressing practice has to be confirmed in reality, especially having in mind the constraints stemming from cold periods: if the SFT level is too high, this can result in an increased risk of track breaking in winter season.

This analysis focuses on the application of speed limits assuming that they are prescribed in accordance to CRT derived as in section 5.3.2. It also illustrates the effects of changing the SFT.

5.5 Methodology, data and assumptions

This research is primarily aimed at assessing future climate change vulnerability, impacts and adaptation measures for the transport sector. For the analysis of the rail buckling problem, this consists in:

- assessing the change in weather conditions in the future and associated risk for rail buckling under current practices and technologies
- Estimating the impact and costs associated with the changing buckling risk
- Analysing some possible adaptation measures and their cost.

5.5.1 Climate indices

Maximum daily temperatures, as projected for the considered scenarios and climate models until 2100 represent the relevant climate data for rail track buckling assessment.. This variable as given for each individual year are used to construct probability distribution functions (pdf) for three intervals (1991-2010, 2041-2070, 2071-2100) and for each 25 km * 25 km grid (or 50 km * 50 km grid for E1 scenarios). As the country SFTs values available are those currently applied, the period 1991-2010 is treated as the control period.

5.5.2 Stress-free temperatures

The data and indications given in section 5.3.1 were used to define assumptions for SFT values in each EU27 country. For the country with reported SFT values, the comparison between corresponding ambient temperature (based on conversion assumption given in section 5.3.2) and the current average maximum temperature for summer period[20] confirms that the SFT is roughly equal to ¾ SFTa[21]. A 0.78 average ratio over the reported countries is derived. The two main exceptions are Spain and UK. For Spain, the ratio is surprisingly 0.66 while for UK, it is ~ 1. Tests shown later highly question the value reported for Spain (Dobney, 2010) as they suggest implausibly high buckling risk. For UK, the value is considered as reliable as it has been reported and referred to in several research papers.

Therefore, the "¾ Tmax" rule is considered as the common rule for each country, except for UK where SFTa is set equal to Tmax. In a later section, sensitivity of rail buckling risk probability to the SFT value is analysed.

	Tmax	Tmin	SFT	SFTa	SFT / Tmax	Tmax*0.75
AT	19.4	-5.7				14.5
BE	20.8	-0.5				15.6
BG	26.3	-2.8				19.7
CZ	21.8	-4.0				16.3
DE	21.6	-2.2	23	15.3	0.71	16.2
DK	19.4	-1.6				14.6
EE	20.1	-8.1				15.1
ES	27.7	1.8	27	18.0	0.65	20.8
FI	18.2	-14.6				13.7
FR	22.9	0.6	25	16.7	0.73	17.2
GR	28.4	1.4				21.3
HU	25.6	-3.3				19.2
IE	18.0	2.0	23	15.3	0.85	13.5
IT	25.2	1.0				18.9
LT	21.2	-7.0				15.9
LU	21.1	-1.3				15.9
LV	20.5	-7.0				15.4
NL	20.8	-0.2	25	16.7	0.80	15.6
PL	22.2	-4.7				16.6
PT	28.0	4.9				21.0
RO	24.7	-5.0				18.6
SE	17.8	-12.0				13.3
SI	23.0	-4.2				17.2
SK	22.7	-5.2				17.0
UK	18.2	0.6	27	18.0	0.99	13.6

Table 23: Key temperature parameter, reported SFT (and SFTa) values and estimated SFT values based on the "¾ Tmax" rule

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[20] Calculated with the A1B-KNMI scenario

[21] SFTa is used to denote the ambient temperature corresponding to the stress free temperature

Table 23 gives the details per country in terms of the annual temperature amplitude[22], SFTs (and corresponding SFTa) for countries documented and estimated SFT value for other countries. Figure 11 shows the same information graphically. It shows more clearly how far the SFTa values provide a balance between hottest and coldest conditions in each country.

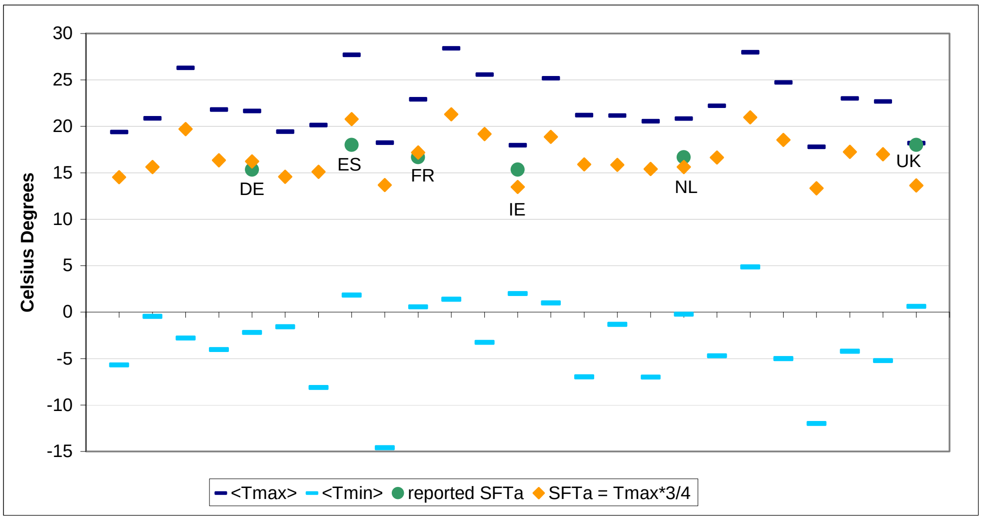

Figure 11: Comparison of reported SFT values with Tmax * ¾

5.6 Results

5.6.1 Exposure and vulnerability

The vulnerability of rail track to buckling is assessed for each 25*25 km grid (50*50 km) in EU27 based on climate scenario data and assumed country SFT values.

To this end, for each grid and time interval, the probability distribution functions (pdf) for maximum daily temperatures are used to calculate the average annual probabilities to have CRT70 and CRT30 exceeded within each grid. These provide indications about current and future risks for rail buckling. Such probabilities are also calculated at country level as the average over the corresponding grids. The results discussed in the following all concern rail buckling for tracks under **inadequate ballast** conditions. Tests indeed showed that such risks are negligible in the case of good ballast conditions.

Figure 12 illustrates the situation expected for one particular grid located in Dordogne NUTS3 (France). The table shows the country stress free temperature and critical temperatures for speed limitations 70 km/h and 30 km/h. Then, for each period, it gives the average annual temperature and average maximum daily temperatures. It then shows the estimated probabilities for the two speed limitations, as well as total occurrence for speed limitation events. The last row corresponds to the period suitable for track maintenance. The first graph shows the probability distribution function for the average maximum daily temperature for the different intervals of time and the second graph shows the estimated probabilities for the two critical temperatures CRT30 and CRT70 to be exceeded.

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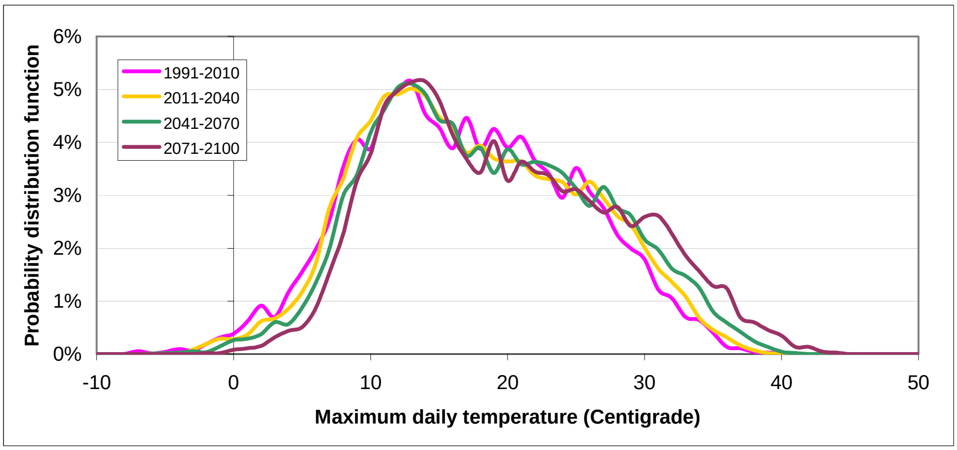
[22] Tmax – Tmin where Tmax is the average maximum daily temperature in summer and Tmin is the average minimum daily temperature in winter.

Climate zone	**France**			
country	**FR**			
NUTS3	**Dordogne**			
Stress free temperature (ambiant, ºC)	17.2			
Critical temperature - 70 km/h (ºC)	25.8			
Critical temperature - 30 km/h (ºC)	27.2			
	1990-2010	2011-2040	2041-2070	2071-2100
average temperature (ºC)	12.0	12.5	13.0	14.0
average maximum daily temperature (ºC)	25.0	25.8	26.6	27.8
probability for 45-90 km/h speed limitation events	6%	6%	6%	6%
probability for 30 km/h speed limitation events	10%	13%	16%	21%
total probability for speed limitation events	16%	19%	22%	27%
period for maintenance (number of days/year)	349	344	334	316



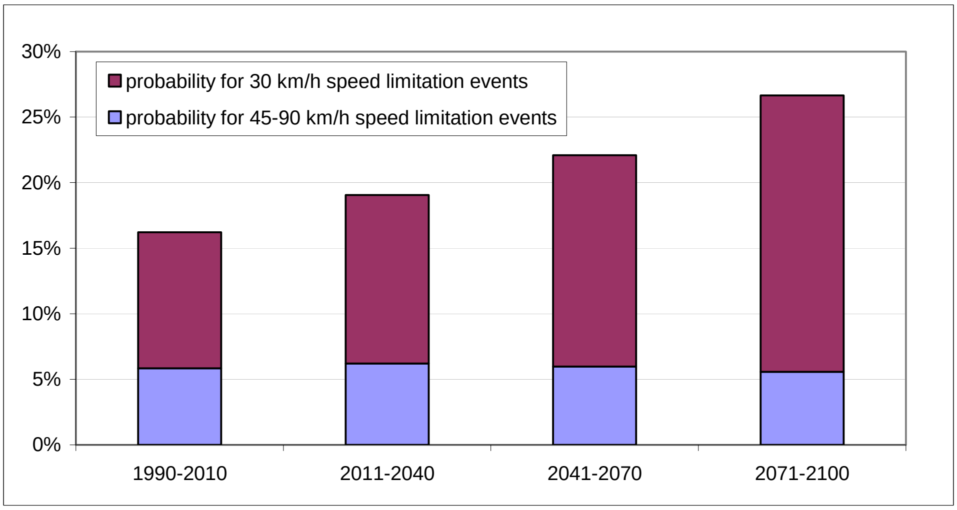


Figure 12: Estimated rail track buckling risk in Dordogne (France)

Probabilities for 75 km/h speed limitations are always much lower than for 30 km/h because the two corresponding CRT are rather close (only 2ºC).

In this specific case, the average maximum temperature is expected to increase by 3.8ºC by 2070-2100 and the probability for Tmax exceeding the critical temperature would increase by 13% by 2100 (47 extra days/year with speed limitation.

The very high frequencies estimated for Dordogne raise the question whether locally warmer conditions are, in practice, used to prescribe higher stress free temperature. In Figure 13, a modified SFT value is considered, consistently with the grid maximum temperature (thus SFTa=18.7 ºC).
The new corresponding speed limitation events probabilities are then significantly decreased (10% instead of 16% initially for the control period). The frequency increases by similar amount as previously.

Stress free temperature (ambiant)	18.7			
Critical temperature (70 km/h)	27.4			
Critical temperature (30 km/h)	28.7			
	1990-2010	2011-2040	2041-2070	2071-2100
probability for 45-90 km/h speed limitation events	2%	3%	3%	3%
probability for 30 km/h speed limitation events	8%	10%	13%	18%
total probability for speed limitation events	10%	13%	16%	21%

Figure 13: Probability for rail buckling related speed limitations in Dordogne under an alternative SFTa value

Quantitative risk estimates for EU27 and for the current period (1990-2010) are summarised in Figure 14. High occurrences for speed restrictions events prevail in several regions (Southern Europe, France) are already suggested for current period. Such high frequencies concern tracks inadequately supported by the infrastructure and ballast. Also, number of days with risk doesn't also mean that speed limits are applied all the day. Important to note is also the fact that the estimates are very sensitive to the SFT values for which assumption were made for a series of countries. This sensitivity is illustrated in Figure 15. Generally speaking, these estimates would need to be compared with real numbers and possibly adjusted. Unfortunately data are not readily available.

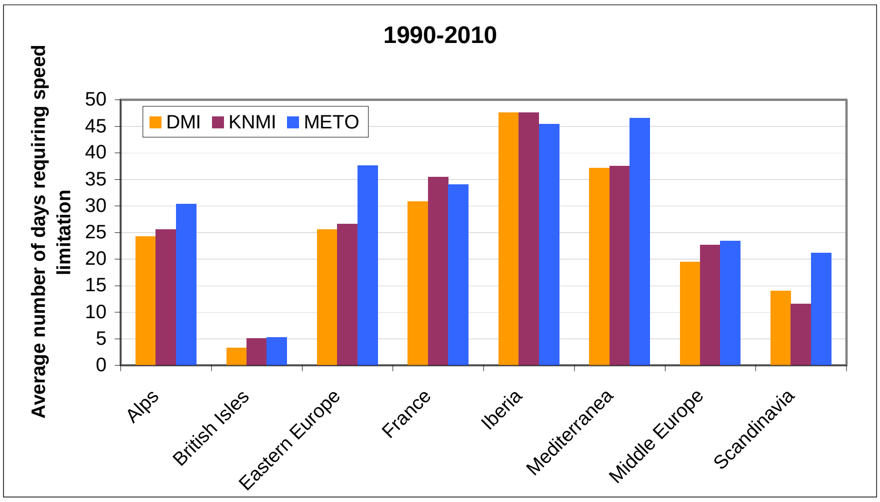


Figure 14: Average frequency of rail buckling risk in the different climate zones in Europe: current estimated risk

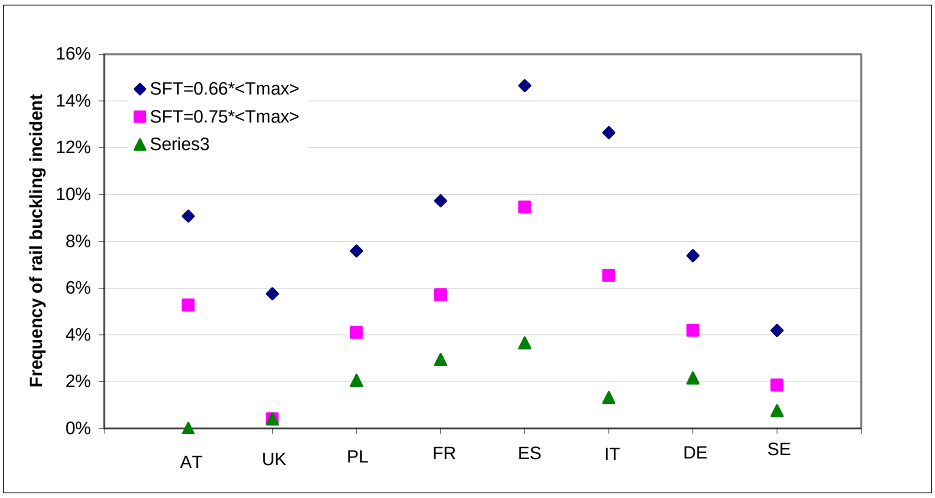


Figure 15: Current estimated frequency of rail buckling incident: Sensitivity to SFT assumption (SFTs are set to 0.66*Tmax, 0.75*Tmax, 0.85*Tmax respectively)

Applying different constant SFTs values doesn't however significantly modify the projected changes in risks. These are summarised in Figure 16, showing the average additional number of days per year with maximum daily temperature exceeding CRT30.

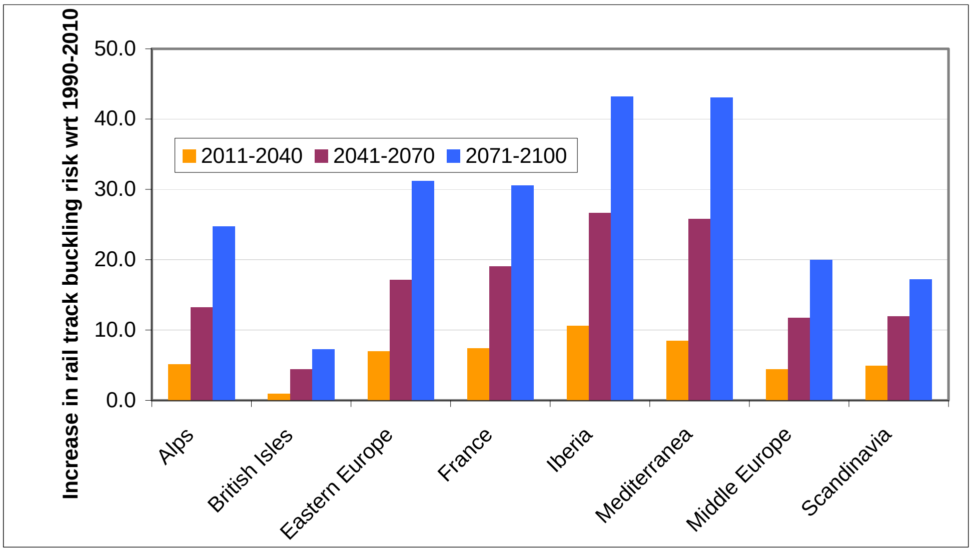


Figure 16: Average annual number of extra days with Tmax over CRT30 in the future, compared with current situation (scenario A1B-KNMI)

Figure 17 geographically represents the same results for the period 2070-2100 as compared with the current situation, for the three A1B climate projections (A1B-KNMI, A1B-METO, A1B-DMI).

The scenario A1B-KNMI shows the highest risk increase in a majority of regions. In all cases, Southern Europe is expected to experience the highest increase risk for rail track bucking. The scenario A1B-KNMI projects the highest increases while the A1B-DMI scenario projects much limited risk increase and in fewer areas.

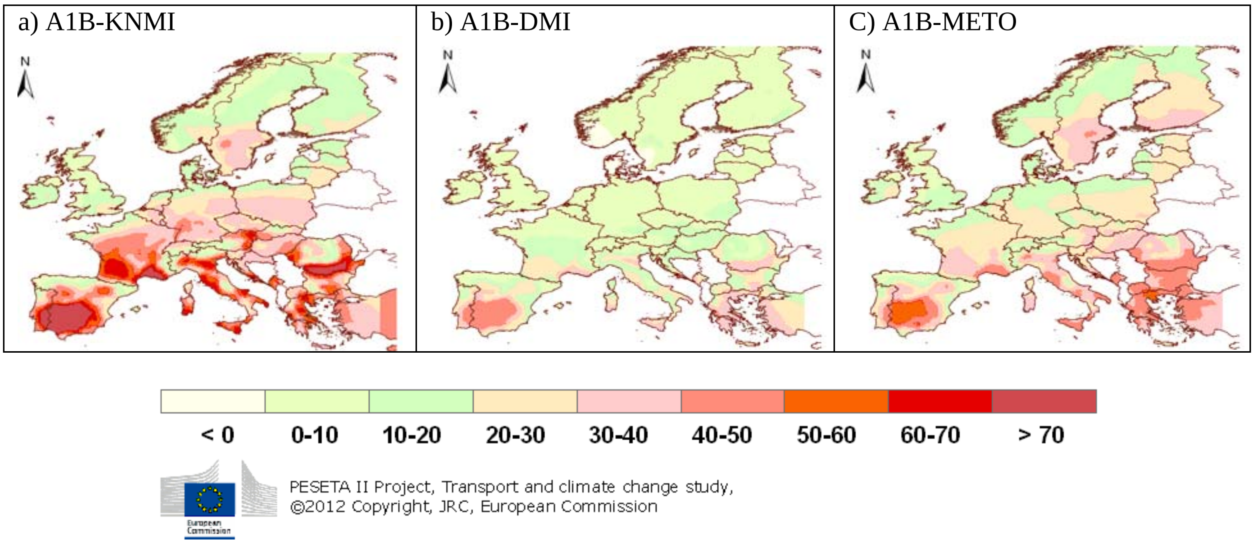


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Figure 17: Vulnerability to rail track buckling: Number of days with Tmax exceeding Critical temperature (CRT70) during 2070-2100 in addition to current situation (1990-2010)

The inter-seasonal maintenance is an important measure to limit track buckling risk. Typical temperature range for normal maintenance is -10ºC - +30º C (Ryan and Hunt)[35]. Previous Figure 12 also provided the estimated length of annual period suitable for track maintenance in the specific case of Dordogne, indicating a significant shortening of maintenance period (-15 days and -30 days/year by 2040-2070 and 2070-2100 respectively). Figure 18 shows the geographical future for the three A1B scenarios. Southern regions will experience a significant decrease in maintenance period while Nordic countries (e.g. Sweden), the milder winters will result in a longer maintenance period. These maps could indicate a future need for Southern Europe to adapt maintenance practices to shorter suitable periods (e.g. increase diurnal periods) and this may represent an additional issue to address in relation with rail track buckling.

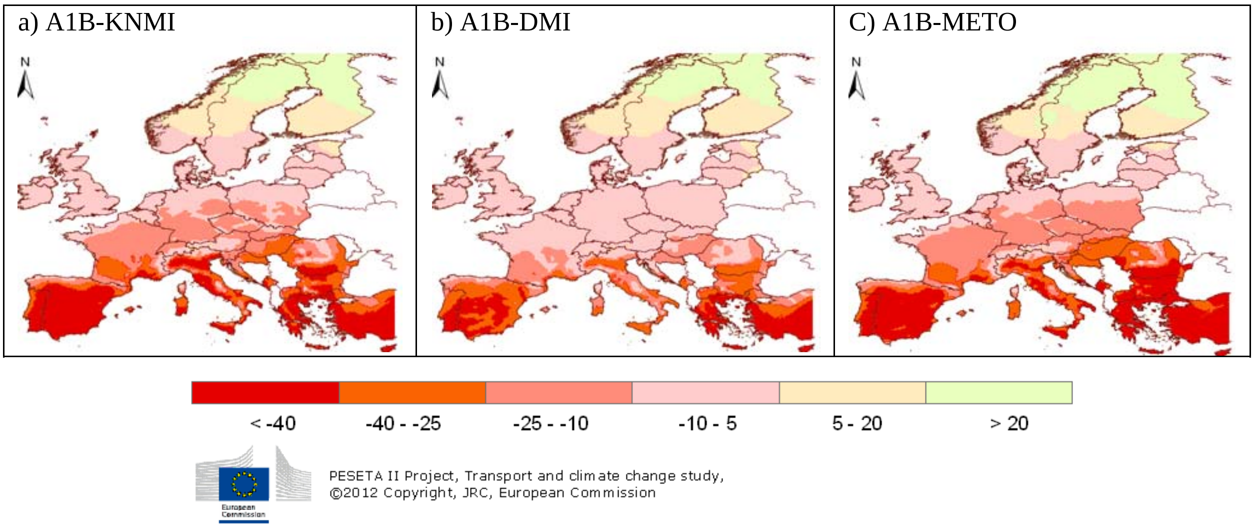

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Figure 18: Vulnerability to rail track buckling: Changes in period suitable for maintenance by 2070-2100 as compared with 1990-2010 for scenarios A1B (number of days in a year)

5.6.2 Cost of adaptation

The above-described estimates for rail buckling risk were used to calculate the annual delays for freight and passenger rail transport. To this end, average free flow speed and total transport activity (pkm, tkm) at NUTS3 level were extracted from TRANSTOOLS model (year 2005).

These were combined with calculated NUTS3 level average occurrences for speed limitation events to derive average annual delay per NUTS3 over the corresponding railway lines, expressed as hour*passenger and hour*ton. Average annual country delays associated with rail buckling risk are then derived.

It was assumed that, long distance and highway lines are always under good quality conditions (~20%) of EU railway network. For the short and medium distance traffic, it was considered that 5**% of rail tracks in the network are sustained by inadequate ballast. Also, speed limits are assumed to be applied during 50% of the daily traffic period (~from 12:00 to 20:00)**. Unfortunately, the absence of a clear definition for inadequate ballast, and the lack of statistical data on heat related delays in Europe make impossible to validate this percentage for EU as a whole.

Several country specific conditions could justify using higher or lower values. For instance, in case of countries / regions with mild winters, inter-seasonal maintenance may be less stringent and ballast is potentially deficient. Other country specific conditions may also be considered, such as the number of tunnels (e.g Austria) under which rail buckling is much lower weather stressed. This needs to be taken into account when interpreting the results.

Table 24 gives the estimated delays for the base year period for the freight transport and passenger transport. These are also expressed as a % of the total free flow speed travel time. On the average, the estimated rail buckling induced delay represents 0.012% and 0.022% of the travel time under optimal traffic (free speed flow traffic) for freight and passenger transport respectively. The percentage largely varies from country to country. Higher percentages are estimated for e.g Italy and Portugal, and, more surprisingly for Austria. Such high numbers should be assessed against real world observations and possibly revisited with more reliable assumptions and technical data (e.g. regionally defined SFT, influence of maintenance, ballast conditions).

	freight		**pass**	
	delays (1000*h)	**% free speed**	**delays (1000*h)**	**% free speed**
AT	182	0.016%	204	0.038%
BE	44	0.012%	81	0.020%
BG	39	0.013%	44	0.016%
CZ	109	0.013%	88	0.013%
DE	506	0.012%	582	0.021%
DK	5	0.004%	40	0.014%
EE	32	0.006%	3	0.006%
ES	116	0.019%	324	0.023%
FI	53	0.011%	37	0.015%
FR	362	0.017%	583	0.027%
GR	6	0.018%	68	0.016%
HU	53	0.010%	95	0.014%
IE	0	0.002%	4	0.003%
IT	211	0.018%	1 056	0.046%
LT	38	0.004%	4	0.009%
LU	3	0.014%	7	0.025%
LV	106	0.013%	9	0.013%
NL	23	0.008%	93	0.013%
PL	259	0.008%	194	0.015%
PT	27	0.021%	97	0.057%
RO	158	0.016%	170	0.026%
SE	107	0.009%	80	0.015%
SI	10	0.006%	5	0.005%
SK	75	0.014%	29	0.018%
UK	15	0.001%	76	0.004%
EU27	**2 537**	**0.012%**	**3 973**	**0.022%**

Table 24: Estimated rail buckling track related delays per year for the period 1990-2010

The delays have been monetarised considering commonly assumed value-of-time assumptions. These assumptions were derived from van Huis (2004)[42] and baseyear estimated shares between business (21 €/hour), commuting (6.4 €/hour) and leisure (3.2 €/hour) taken from the TREMOVE model. From this an average value for time (8 €/hour) was derived. For freight, the average value (0.76 €/ton/hour) was considered.

Resulting costs estimates are shown in Table 25. They provide the average estimates over the three A1B scenarios (A1B-KNMI, A1B-METO, A1B-DMI) for the current period, and future periods (7 first columns). In total, current estimated delay cost for Europe is ~34 million €, in which Italy, Spain, France, but also Germany are the main components. These high shares have to be interpreted with caution, keeping in mind the above- mentioned sources of uncertainties. Future costs are projected to increase all over Europe (+60% and 104% by 2040-2070, 2070-2100, with respect to current costs).

	1991-2010	2040-2070			2070-2100			2070-2100 (changing SFT		
	annual delay cost (million euro)	annual delay cost (million euro)	additional delay cost (million euros)	% cost increase	annual delay cost (million euro)	additional delay cost (million euros)	% cost increase	annual delay cost (million euro)	additional delay cost (million euros)	% cost increase
AT	1.8	2.5	0.8	44%	3.2	1.4	79%	2.4	0.6	34%
BE	0.7	1.0	0.3	44%	1.2	0.5	81%	0.9	0.2	33%
BG	0.4	0.7	0.3	83%	1.0	0.6	147%	0.6	0.2	55%
CZ	0.8	1.2	0.4	52%	1.6	0.8	102%	1.2	0.4	53%
DE	5.0	7.6	2.5	50%	9.3	4.3	85%	7.0	1.9	38%
DK	0.3	0.5	0.2	48%	0.6	0.2	74%	0.4	0.1	29%
EE	0.0	0.1	0.0	74%	0.1	0.1	112%	0.1	0.0	41%
ES	2.7	4.3	1.7	62%	5.5	2.8	104%	4.3	1.7	62%
FI	0.3	0.6	0.3	75%	0.6	0.3	91%	0.5	0.1	36%
FR	4.9	8.0	3.1	62%	10.1	5.1	104%	7.4	2.5	50%
GR	0.6	1.0	0.4	79%	1.3	0.8	141%	0.8	0.2	44%
HU	0.8	1.4	0.6	79%	2.0	1.2	152%	1.3	0.5	64%
IE	0.0	0.1	0.0	110%	0.1	0.1	165%	0.1	0.0	116%
IT	8.6	14.4	5.8	67%	18.4	9.8	113%	12.2	3.6	42%
LT	0.1	0.1	0.0	62%	0.1	0.1	96%	0.1	0.0	42%
LU	0.1	0.1	0.0	36%	0.1	0.0	60%	0.1	0.0	27%
LV	0.2	0.3	0.1	65%	0.3	0.2	104%	0.2	0.1	55%
NL	0.8	1.1	0.4	47%	1.4	0.6	81%	1.1	0.4	49%
PL	1.7	2.7	0.9	53%	3.4	1.6	93%	2.6	0.8	47%
PT	0.8	1.2	0.4	56%	1.6	0.8	98%	1.1	0.3	38%
RO	1.5	2.4	0.9	63%	3.2	1.7	114%	2.2	0.7	47%
SE	0.7	1.2	0.5	68%	1.5	0.7	101%	1.0	0.3	39%
SI	0.0	0.1	0.0	89%	0.1	0.1	164%	0.1	0.0	53%
SK	0.3	0.5	0.2	62%	0.6	0.4	126%	0.4	0.2	54%
UK	0.6	1.0	0.4	68%	1.5	0.9	147%	1.1	0.4	70%
EU27	**33.7**	**54.0**	**20.3**	**60%**	**68.7**	**35.0**	**104%**	**49.0**	**15.3**	**45%**

Table 25: Estimated cost of delays due to rail track buckling speed limits for the A1B scenarios (assuming constant SFT values – 7 first columns - and changing SFT according to new extreme temperatures (last 3 columns)

For comparison, the estimated delay costs for scenarios E1 and RCP8.5 are shown in next tables. This shows that costs estimated for the three scenarios A1B, E1 for the period 2040-2070 do not significantly differ. The costs for the scenario RCP8.5 are ~30% than for the average costs for A1B. Difference in delay costs are much more pronounced for the second period (-25% and +270% for scenarios E1 and RCP8.5 respectively compared to A1B average costs).

As mentioned previously, changing the SFT level in accordance to new temperature profiles could be an option to reduce rail buckling risk, and thus reduce needs for speed restrictions. The consequences of such an option are shown in the 3 last columns from Table 25 for the period 2070-2100. This shows that, delay costs increase could potentially be more than halved. Cost information of such a measure is not available. Its implementation may be limited by the need to maintain a good compromise between coldest and hottest temperatures conditions and speed limit restriction, combined with improved maintenance practices and weather forecast may represent a more cost-efficient measure to mitigate derailment risk.

	1991-2010	2040-2070			2070-2100		
	annual delay cost (million euro)	annual delay cost (million euro)	additional delay cost (million euros)	% cost increase	annual delay cost (million euro)	additional delay cost (million euros)	% cost increase
AT	1.8	2.2	0.4	22%	2.3	0.5	30%
BE	0.7	0.8	0.2	23%	1.0	0.3	42%
BG	0.4	0.6	0.2	46%	0.6	0.3	67%
CZ	0.8	0.9	0.1	13%	0.9	0.1	17%
DE	5.0	6.3	1.3	25%	6.9	1.9	37%
DK	0.3	0.4	0.1	21%	0.4	0.1	31%
EE	0.0	0.1	0.0	75%	0.1	0.1	109%
ES	2.7	5.6	2.9	109%	6.9	4.2	156%
FI	0.3	0.4	0.0	13%	0.4	0.0	14%
FR	4.9	9.2	4.2	86%	9.6	4.7	95%
GR	0.6	0.8	0.3	54%	1.1	0.6	104%
HU	0.8	1.1	0.3	38%	1.3	0.5	58%
IE	0.0	0.0	0.0	24%	0.0	0.0	29%
IT	8.6	17.5	8.9	104%	18.5	9.9	115%
LT	0.1	0.1	0.0	24%	0.1	0.0	32%
LU	0.1	0.1	0.0	21%	0.1	0.0	25%
LV	0.2	0.2	0.0	26%	0.2	0.1	42%
NL	0.8	1.1	0.3	39%	1.2	0.4	51%
PL	1.7	2.3	0.6	34%	2.7	1.0	55%
PT	0.8	1.1	0.3	42%	1.3	0.5	69%
RO	1.5	1.8	0.4	24%	2.0	0.5	34%
SE	0.7	0.8	0.1	17%	0.9	0.1	21%
SI	0.0	0.1	0.1	119%	0.1	0.1	159%
SK	0.3	0.4	0.1	43%	0.5	0.2	71%
UK	0.6	0.8	0.1	23%	0.9	0.2	38%
EU27	**33.7**	**54.7**	**21.0**	**62%**	**60.0**	**26.3**	**78%**

Table 26: Estimated cost of delays due to rail track buckling speed limits for the E1 scenarios (assuming constant SFT values – 7 first columns - and changing SFT according to new extreme temperatures (last 3 columns)

	1991-2010	2040-2070			2070-2100		
	annual delay cost (million euro)	annual delay cost (million euro)	additional delay cost (million euros)	% cost increase	annual delay cost (million euro)	additional delay cost (million euros)	% cost increase
AT	1.8	2.6	0.8	45%	3.8	2.0	112%
BE	0.7	1.0	0.3	49%	1.7	1.1	155%
BG	0.4	0.7	0.4	91%	1.2	0.8	203%
CZ	0.8	1.1	0.3	38%	1.3	0.5	66%
DE	5.0	7.5	2.4	48%	11.8	6.8	135%
DK	0.3	0.4	0.1	38%	0.6	0.3	100%
EE	0.0	0.1	0.0	77%	0.2	0.1	263%
ES	2.7	4.2	1.5	57%	10.5	7.8	292%
FI	0.3	0.4	0.1	31%	0.5	0.2	48%
FR	4.9	7.0	2.0	41%	14.0	9.1	184%
GR	0.6	1.3	0.7	129%	2.7	2.2	399%
HU	0.8	1.4	0.6	80%	2.1	1.3	167%
IE	0.0	0.1	0.0	45%	0.1	0.0	91%
IT	8.6	23.0	14.3	167%	95.2	86.6	1006%
LT	0.1	0.1	0.0	51%	0.1	0.1	94%
LU	0.1	0.1	0.0	25%	0.1	0.1	86%
LV	0.2	0.2	0.1	60%	0.4	0.3	171%
NL	0.8	1.0	0.2	32%	1.8	1.1	141%
PL	1.7	3.0	1.2	70%	5.3	3.6	205%
PT	0.8	1.3	0.5	68%	2.6	1.8	223%
RO	1.5	2.5	1.0	68%	3.5	2.0	137%
SE	0.7	1.0	0.2	32%	1.2	0.5	63%
SI	0.0	0.1	0.1	117%	0.3	0.2	424%
SK	0.3	0.5	0.2	74%	0.9	0.6	203%
UK	0.6	0.8	0.2	32%	1.4	0.8	130%
EU27	**33.7**	**61.3**	**27.6**	**82%**	**163.4**	**129.7**	**385%**

Table 27: Estimated cost of delays due to rail track buckling speed limits for the RCP8.5 scenarios (assuming constant SFT values – 7 first columns - and changing SFT according to new extreme temperatures (last 3 columns)

5.7 Concluding remarks

The rail track buckling is a problem of a high technical complexity devising intense engineering research. This issue has gained some concern in the climate change and transport related literature since the 2003 summer during which serious problems were experienced in United Kingdom. This problem thus devised this EU-wide analysis.

Future rail track buckling risk will depend on several factors such as inter-season climate variability, summer temperatures, maintenance practices and weather forecasting capabilities and will be significant one some limited parts of the rail network.

This research concludes that the most commonly applied measure to mitigate rail derailment in case of buckling risk, namely speed restriction, represent a minor share (~0.01%) of the currently estimated travel time for passenger and goods transport. In monetary terms, this represents ~34 million €/yr. Under unchanged maintenance practices, the extra cost resulting from warmer summer conditions could be 20-28 million €/yr by 2040-2070, with only a small variation across different emission scenarios. By 2070-2100, this extra cost could be from ~50 million €/yr to 130 million €/yr for the A1B and RCP8.5 scenarios respectively. In a 2ºC scenario the costs will remain comparable to the earlier period.

The analysis also suggests that the needs for speed restriction in case of buckling risk, and resulting trip delays could significantly be reduced (more than halved) by changing the track anchoring conditions (adapting stress-free temperature to higher summer temperatures). However, the feasibility and costs of such a measure needs to be assessed. First, the anchoring and maintenance conditions have to be adapted not solely to the summer conditions, but also to the annual temperature amplitude. Second, cost data for such a measure was not available and, also, this possibility is also almost not discussed in the reviewed literature. Experts in the field consulted during this research didn't provide any insight regarding the need and / or feasibility of that measure.

The inherent technicality and very locally influencing factors make such a EU-wide analysis challenging and necessarily simplistic. Despite these simplifications, this study provides some evidence that rail track buckling risks will increase in the future and that speed limitations, improved weather forecast and adequate inter-season maintenance will help addressing that risk. This would certainly benefit from the intra-EU exchanges of good practices.

Another linked aspect is the likelihood that future climate changes will imply adaptation of the maintenance time-schedule, especially in Southern countries where summer conditions unsuitable for maintenance activities will be more frequent.

6 Adaptation to more extreme precipitations: Bridge scour

6.1 Problem description

River bridges represent essential components of transport network. Both bridge structure load and traffic load often require placing vertical columns or piers in the river. In the same time the bridge piers – and abutment – represent a challenge for bridge engineers as they induce complex flow-structure sediment interactions. The risk associated with such complex interactions is referred to as bridge scour.

Basically, "***Bridge scour*** *is the removal of sediment from around bridge abutments or piers. Scour, caused by swiftly moving water, can scoop out scour holes, compromising the integrity of a structure. Bridge scour is basically induced by the fact that water normally flows faster around piers and abutments making them susceptible to local scour. Bridge scour is one of the three main causes of bridge failure. It has been estimated that 60% of all bridge failures result from scour and other hydraulic related causes. It is the most common cause of highway bridge failure in the United States,*[1] *where 46 of 86 major bridge failures resulted from scour near piers from 1961 to 1976.*" [23]

Although bridge scour has been observed since a long time, the full understanding of the physicals governing the mechanism is relatively recent. (Chiew Y, 2008)[24]. Damages on bridges, and induced bridge scour mainly occur during flood events (Bruce et al, 2000)[43]. All over Europe, bridge scour is reported as one of the most important problems for railway bridge substructures (Bell, 2004)[44]. In US, the impact of the hurricane Katrina has been very important, including scour effect. The average flood damage per bridges has been estimated to ~1.4 million USD/bridge (Padgett et al, 2008)[45].

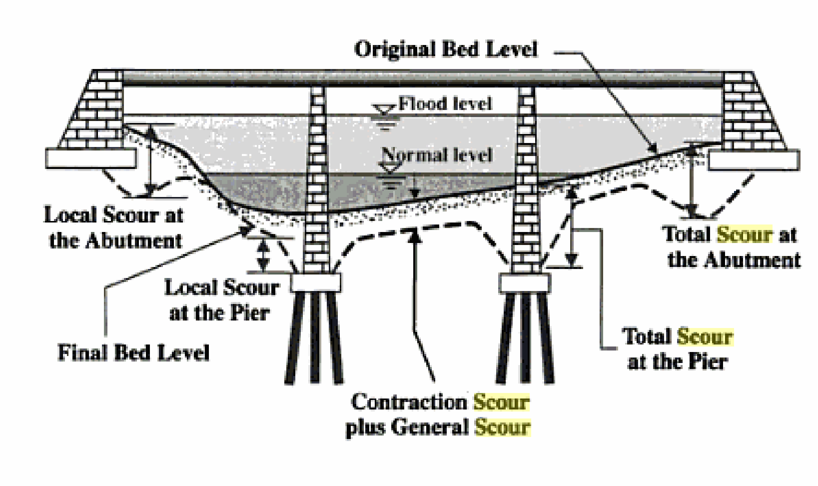

Figure 19 : Types of bridge scour
(from Melvile et al, 2000)[43]

Under the future climate change, some regions in Europe will face changing precipitation regimes and altered snow melting patterns. This, in some areas will result in higher flood frequencies and or intensities. Building upon the analysis performed under the flood analysis (Feyen et al, 2012) [4], this chapter provides a first order assessment of the future vulnerability of bridges to scour as induced

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[23] http://en.wikipedia.org/wiki/Bridge_scour

by changing river floods intensities. It also performs a rough assessment of the most common measures which would be applied to prevent the risk as anticipated by 2040-2070 and by 2070-2100. These measures consist in riprap and in reinforcing the foundation with concrete.

Riprap represents the most common countermeasure used to prevent scour at bridge abutments. It consists in placing large blocks at the base of the bridge piers to protect the foundation footings and piers from the direct impact of water flow. Beyond water velocities of 12 and 10 km/h for sand and non sandy material respectively, riprap measures become ineffective and foundations need to be strengthened (additional concrete around foundation).

The next sections present the methodology and results on vulnerability and on costs.

6.2 Methodology, data and assumptions

6.2.1 Methodology

The applied method is to a large extent based on a study conducted by the US Environmental Protection Agency (EPA) to analyze the vulnerability of bridges to increased floods in US as a result of climate change (Wright et al, 2012)[46].

In that study, future 24h peak river flow rates were calculated for the 100-year return period from GCM rainfall prediction in the continental United States. This was combined with information from the US National Bridge Inventory (NBI) database to estimate increased bridge vulnerability. The distinction between river bed types (sandy / non sandy) was also made to reflect its influence on critical water velocities above which the bed material is transported (5.5 and 7.7 km/h for sand and non-sand material respectively). At these flow velocities, the potential exists for scour to occur around bridge foundations. Bridges were characterized into deficient and acceptable ones, using different criteria measured in the NBI.

The detailed data per bridge contained in the NBI database (e.g. physical conditions on substructure, water flow and channel, waterway opening, vulnerability to scour) was used by the EPA to characterise the different bridges, including their level of deficiency of bridges. The vulnerability was assessed and damage costs were derived by combining this bridge characterisation with the projected river flows.

The percentage changes in 100-yr return peak flow by 2046-2065 and 2080-2100 compared with historical data were used to determine the scouring risk and need for one of the two adaptation measures, namely riprap and concrete reinforcement of foundations. The approach is based on the following key assumptions:

- Under **less than 20%** change in 100-yr return peak flow by the beginning of the period, the initial bridge design is still adequate and no measure is needed.

- Under changes **higher than 20%,** measures are required to prevent bridge scour and this depends on the river bed material:
  - **Riprap** is the first adaptation measure and it is adequate up to a certain flow change (**60% and 100% change** for non sandy and sandy soils respectively).
  - Beyond these thresholds, the foundation needs to be reinforced with **concrete**.

The initial profile of the bridge also determines the subsequent measure: if the bridge is assessed to be currently deficient (poor substructure condition, undermined bank or embankment protection, bridges overtopped every 1/11 year, vulnerability to scour) it is assumed to be repaired immediately and associated costs are not attributed to climate change.

For **the cost calculation**, following assumptions are made:

- Riprap:

$$\text{Cost} = U1 \times L \times (S-1)$$

- Concrete strengthening:

$$\text{Cost} = U2 \times L \times W \times SL$$

Where

U1 and U2 are unit costs (U1~173 00€/riprap [24] and U2 is the Unit cost for concrete reinforcement per one square meter of bridge deck (~250 €/m2))
L = Number of lanes on bridge,
S is the number of piers,
W is the Width of a single lane (~5 m),
SL = Total span length of the bridge.

6.2.2 Data and key assumptions

For conducting the analyses for Europe, the changes in the peak river flows were provided by the PESETAII river floods study based on the LISFLOOD hydrological model (see Feyen et al (2012)[4]. Due to the highly time-consuming data processing, this adaptation case study has been performed only for one scenario (A1B-KNMI) for which the 100-yr maximum river flows, for the intervals 1961-1990, 2041-2070 and 2071-2100 have been used. The 100-year flow generally represents a maximum flow that many bridges were designed to withstand.

While having these detailed river flood simulation, the analysis had to cope with the lack of EU-wide bridge inventory including the locations. In order to fill this gap, spatial analysis was performed to infer the existence and location of river bridges. The rough analyse consists in spatially overlaying the main water bodies, lakes, rivers, etc with EU-wide main railways and roads. The Eurostat spatial database, the Geographical Information System at the Commission (GISCO), was applied. Domains were classified according the INSPIRE[47]. The scale was 1: 1 million, where the coordinate reference system was the European Terrestrial Reference System 1989 (ETRS89). Bulgaria could not be covered as the water bodies within the GISCO dataset are missing.

Inferred bridges were also indirectly characterized in terms of river bed soil type by overlaying the geo-referenced European Soil Database (ESDB)[25] available for 1 km x 1 km raster data sets.

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[24] The cost data from US study were converted into € (1€~1.3 USD)

[25] From the database mainly surface textural class was used, where soil types were classified as; Peat soils, Coarse (18% < clay and > 65% sand), Medium (18% < clay < 35% and >= 15% sand, or 18% < lay and 15% < sand < 65%, Medium fine (< 35% clay and < 15% sand), Fine (35% < clay < 60%) and very fine (clay > 60 %).

(Panagos et al., 2012)[48]. Two groups of soils were defined: sandy (including peat), coarse and medium - and non sandy – medium fine, fine and very fine.

The derived bridge inventory was rescaled by using the information from the EU-Cost project (COST 345 EU project, 2012) [49] applied in 10 countries on bridges (see next section).

6.3 *Results*

6.3.1 Bridge inventory

Based on the spatial analysis, a total of 54 674 bridges were identified, of which 10 239 rail bridges and 44 435 road bridges. While this inferring method has the advantage of providing a coarse localization of main bridges, it had to be corrected with data available for some countries. The COST345 study reports data for all types of bridges for a dozen of EU countries, including bridges for national, regional and secondary roads.

Considering the total bridges for national and regional roads and comparing with the inferred stock for the available countries results in an average factor of 13. Assuming that 50% only of the reported bridges are crossing rivers, the scaling factor to be considered is 6.5.

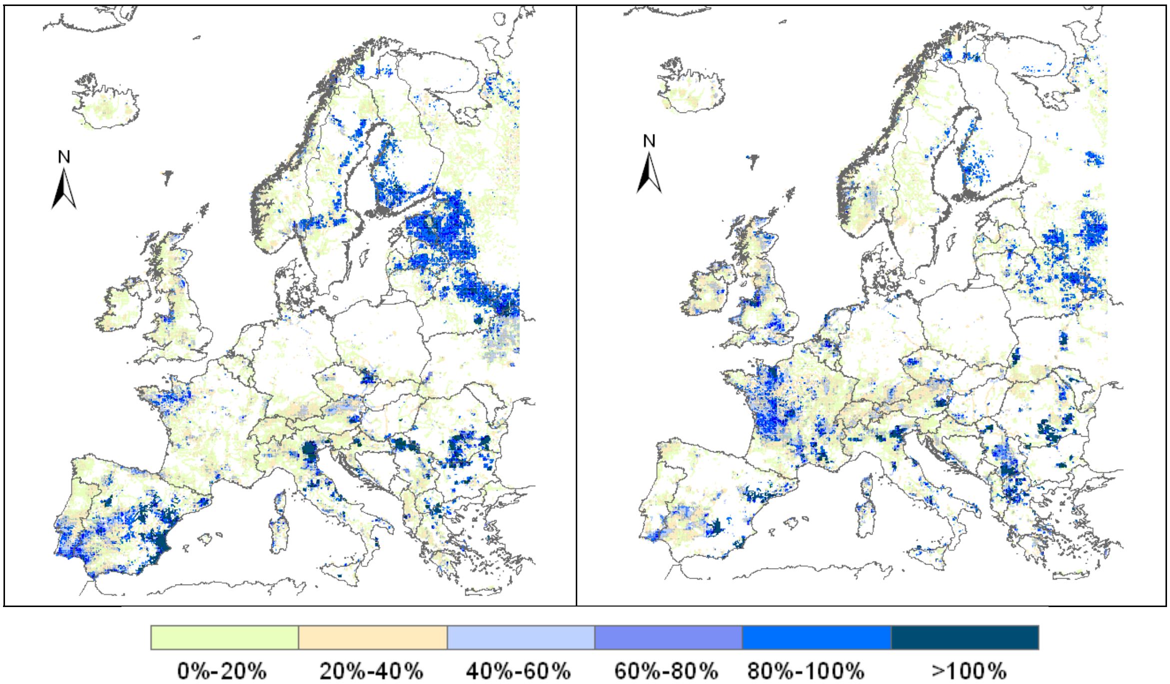
Similar correction can be inferred when considering the total bridge stock for US (713000, of which 485000 are crossing rivers). EU territory is about half of US territory, suggesting that bridge stock for EU would be around 240000. This also suggests a rescaling factor of ~6.

	Own estimates	**Reported**		**ratio estimate/total reported**
		National roads	**Regional roads**	
AT	822	4 383	7 137	14.0
CZ	1 390	3 579	4 468	5.8
DE	6 914	41 222	60 000	14.6
DK	294	1 375	3 300	15.9
FR	4 378	28 850	85 000	26.0
IE	360	1 853		5.1
PL	3 413	3 517	3 491	2.1
SI	410	981	954	4.7
SE	6 383	3 750	3 750	1.2
UK	2 417	15 992	77 692	38.8
Total	**26 781**	**105 502**	**245 792**	**13.1**

Table 28: Comparison between inferred bridge stock (own estimation) and reported data (in COST 345 project)

6.3.2 Exposure and vulnerability

Figure 20 provides a map to illustrate the level of vulnerability for bridge scour in the different zones in Europe for the periods 2040-2070 and 2070-2100. It represents the percentage of increase in 100-yr-return peak river flow. In total, ~20% of bridges are estimated to be at risk over one of the two periods. This percentage changes from one country to the other and the risks are estimated to be highest in Austria (60%), Portugal (50%), Spain (42%) and Italy (39%).



PESETA II Project, Transport and climate change study,
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Figure 20: Vulnerability of bridges to scour
(percentage of increase in 100-yr-return peak flow by 2041-2070 and 2071-2100, respectively)

6.3.3 Cost of adaptation

The above-described approach was applied to estimate costs to adapt bridges in order to mitigate bridge scour risk. These annual costs are given in Table 29 for the two periods 2040-2070 and 2070-2100 respectively. The costs are aggregated into main climate zones. In total annual (non discounted costs) are estimated to ~541 million €/yr and 382 million €/yr respectively. In these costs are shared into road bridges (80%) and rail bridges (20%). In the case of road bridges the costs to protect bridges corresponds to 1.5% to 2% of current road maintenance costs.

Further detailed risk analysis would be necessary to provide an estimate of the costs which would be avoided by the assumed preventive measures. It is to be noted that a bridge failure can easily represent 2 to 10 times the bridge reconstruction (Idaho Transportation Department, 2004)[50]

	2040-2070	2070-2100
0	24.7	22.5
Alps	93.9	97.4
UK & Ireland	47.4	25.0
Eastern Europe	90.8	91.3
France	79.4	32.7
Iberia	91.1	51.6
Mediterranea	41.1	38.9
Middle Europe	72.8	23.5
Total	541.3	382.7

Table 29: Cost of adaptation to reduce the risk of bridge scour for the periods 2040-2070 and 2070-2100 (million €/yr)

6.4 Concluding remarks

This study is an initial quantitative assessment about the future vulnerability and adaptation of river bridges under future climate changes and changing river peak discharge patterns. It suggests a significant cost resulting from the retrofitting of bridges with protection measures to cope with projected changes in 1/100 yr river discharge in several parts of Europe.

This assessment is based on different types of assumptions (some of them taken from United State more detailed analysis, other build upon spatial analysis), and upstream research inputs (e.g. on flooding). Much more detailed analysis would be essential to provide more robust assessment at regional level which should also complemented with a wider range of climate scenarios.

Based on this present study, the future cost for bridge protection against scour risk is estimated to about 0.38 and 0.54 billion €/yr, composed of costs for road bridges (80%) and rail bridges (20%). In the case of road bridges, this corresponds to 1.5% to 2% of current maintenance costs.
The damage costs (bridge collapse and possible accidents, injuries and fatalities, and subsequent costly repairing or reconstruction) avoided by implementing this protection measure was not assessed.
"*However, the added cost of making a bridge less vulnerable to scour is small compared to the total cost of failure, which can easily be 2 to 10 times the cost of the bridge itself" (Idaho Transport Department)*[50].

Bridges are designed for long life spans (>100 years) and their maintenance and repairing activities have to be planned long time in advance. Future climate-related risk should be included in corresponding prior cost-benefit studies.

7 Infrastructure vulnerability: sea level rise and sea storm surges

7.1 Problem description

This chapter analyses the future impact of sea level rise on transport infrastructures. Sea-level rise (SLR) and sea storm surges will result in coast erosion and coast retreat. More transport infrastructure (together with built infrastructures and residence) will be at risk of temporary and permanent flooding.

The 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) projects global mean sea level rise in a **18–59 cm** range, above 1990 levels by the 2090s. The IPCC also found that sea level rise could be greater than the global average around northern Europe, by an additional 15–20 cm due to changing climate patterns (air and water currents), reaching up to 38–79 cm around e.g. Denmark. Local SLR will actually vary with ocean circulation patterns, gravitational effects, land subsidence or uplift along some coastlines, and other factors. Also, whereas sea level rise is already ongoing, it can only partly be attributed to global human-created climate change. For instance, von Storch at al (2008) argue that the main part of the observed increase in Hamburg is due to improved coastal defence. Another cause is the dredging of the shipping channel.

It has to be noted that the IPCC AR4 projections do not fully include contributions from the melting ice sheets. More recent studies (e.g., Rahmstorf (2007)[51], Pfeffer et al. (2008)[52] suggest higher global sea level rise (**50-200 cm** above 1990 levels by 2100).

Storm surge is the water surface response to wind-induced surface shear stress and pressure fields caused by storms. Water level is increased due to the low pressure at the centre of the storm drawing water upward and the strong winds pushing the sea surface and effectively creating a large wave. This is known as 'wave set up' and is generally the most destructive component of storms (in comparison to wind), as illustrated by the extensive damage caused by Hurricane Katrina's storm surge. (Hallegatte et al, 2008)[53].

Climate change can induce changes in the characteristics of extra-tropical cyclones, including frequency and intensity, thus potentially increasing the risks associated with storm surges.

In Europe, a number of studies, using either statistical or dynamical approaches demonstrate how an increase of up to 10% in extreme wind speeds in the North Sea and the Norwegian Sea may take place when CO2 concentrations are doubled (B2) or almost tripled (A2). These changes suggest an increase in surge-height extremes of the same proportion (Von Storch, Woth, 2008)[15]**.** Woth et al. (2006) found that, for the North Sea, a 100-year event could become 10–20 cm higher than today by the 2080s. Also, In the Baltic Sea, Meier (2006) found that water levels associated with a 100-year event increase more rapidly than increases in mean sea levels.

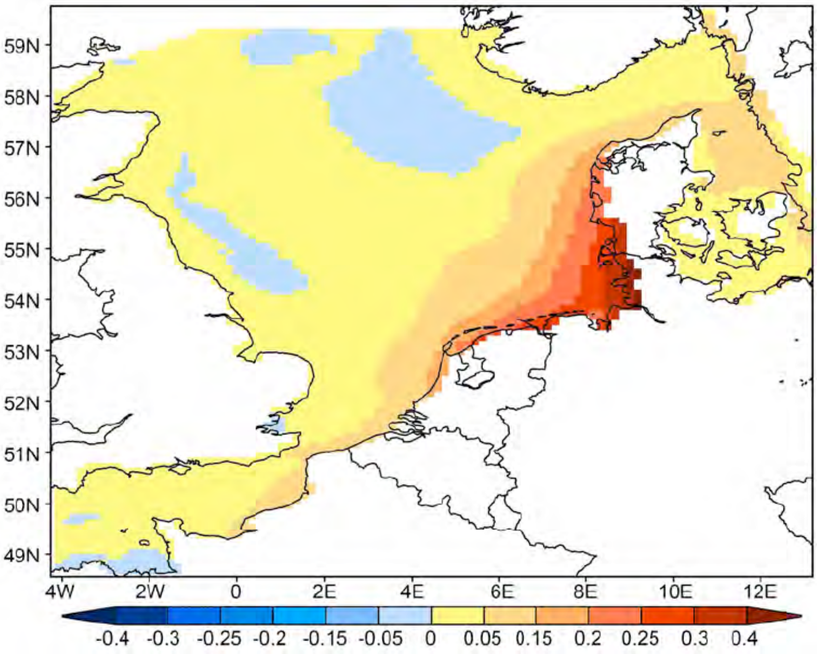

Fig. 3: Changes of the 30 winter mean of the annual maximum of high waters [m] in the A2-scenario projected for 2071-2100, as simulated by TRIMGEO in response to RCAO winds

Figure 21: Water levels along North sea coast by 2070-2100
Source : Grossmann et al[54]

7.2 Exposure and vulnerability

This analysis represents a first attempt to assess the vulnerability of transport infrastructure to sea level rise, with particular focus on transportation at coastal zones. A **1 meter sea level rise by 2100**, was considered, separately and combined with different sea storm surge intensities. Given the lack of EU-wide estimates, **sea storm surge height** (e.g. 100-yr return period value) is assumed unchanged compared to today (see section on data).

This section summarizes the applied methodology and major findings in terms of vulnerability.

The two sets of assumptions on SLR and sea storm surge heights (added to the maximum tide wave) provide corresponding thresholds for elevation below which areas are under risk of temporary (due to sea storm surges) or permanent (due to sea level rise) inundation.

The "bucket fill" approach was applied in order to determine the areas that would be inundated in case of sea level rise and sea storm surge. This approach assigns the water level by means of projecting it on Digital Elevation Model (DEM). This approach is considered robust for such a first order risk analysis (DCC-AG, 2009)[55]. This methodology has been applied in recent international studies on determining the impacts of sea level rise including transportation[56, 57, 58].

The two types of inundated areas (permanently or temporarily) are then overlaid with the transport network infrastructure, to identify the linear distance in kilometers affected within each scenario. The airports, runways and port areas were also intersected with these areas to be able to identify the number and the area in km^2 affected under each scenario.

Three main data sources were used to implement the approach:

- **Digital Elevation Model (DEM):** The Shuttle Radar Topography Mission (SRTM) data from NASA, USA was used. It is the best available, publically accessible and global ranged elevation data. (http://srtm.csi.cgiar.org/) The horizontal resolution is 90 meters. Although, some vertical accuracy concerns rise, the SRTM data is generally used for sea-level rise studies requiring global coverage (CCSP, 2009)[59]. From the SRTM data, after processing and masking, DEM of the coastal zone and the coastline were retrieved. For some areas, where SRTM is not available - such as Finland - , the GTOPO30 global Digital Elevation Model was applied. That model has horizontal grid spacing of 30 arc seconds (approximately 1 kilometer) and was derived from a variety of raster and vector sources. The data is expressed in geographic coordinates and is referenced to the World Geodetic Survey (WGS) system of 1984 (WGS84). Data is freely available[26].

- **Coast line attributes and sea storm surge:** The Dynamic Interactive Vulnerability Assessment (DIVA) database was used (Vafeidis et al. 2008)[60], [27]. The DIVA model was produced by the he EU-funded project DINAS-COAST (Hinkel 2005[61]) to assess impacts and vulnerability to sea-level rise at scales from coastal segment up to global. In addition to coast line segment attributes, surge heights for 1-in-1-year (S1), 10-in-1-year (S10), 100-in-1-year (S100) and 1000-in-1-year (S1000) were assigned to coastal segment.

- **Transport infrastructure:** For road infrastructures, Teleatlas[28] data was used. It is a very rich and accurate dataset. Motorways, major and secondary roads were selected.

One important source of uncertainty and inaccuracy is the fact that the data sources do not provide detailed information about current protection (dikes, dunes). Also, the elevation of infrastructure is not taken into account when generating the inventory of network at risk. This means that the approach could potentially overestimate risks for such infrastructures. Also, the largest inaccuracy is expected for the low-lying countries and regions (Netherlands, northern parts of Belgium and of Germany).

On the other hand, while sea level rise is gradual, built areas, including road and railway embankment might also gradually be subject to erosion. In addition, this study does not capture hydraulic process, such as the width and depth of channels, where the EU-wide information is not available.

Figure 22 presents a sample coastal zone (South Portugal) with the simulated areas at risk of inundation. For simplifying, only the major road network is presented. Areas below the current sea level according to DEM projection are illustrated in blue. These areas do not adequately reflect the current situation because of uncertainties associated with e.g. boundary determination, inadequate spatial resolution or lack of information on existing coast protection. In the second figure, both current and 1 meter sea level levels (orange) are overlaid. The figure c) represents both areas at risk of permanent and episodic inundation as a result of a 100-yr return sea storm surge (in magenta).

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[26] (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/GTOPO30

[27] DIVA database was retrieved from http://diva.demis.nl/

[28] http://www.tomtom.com/en_gb/licensing/products/maps/multinet/

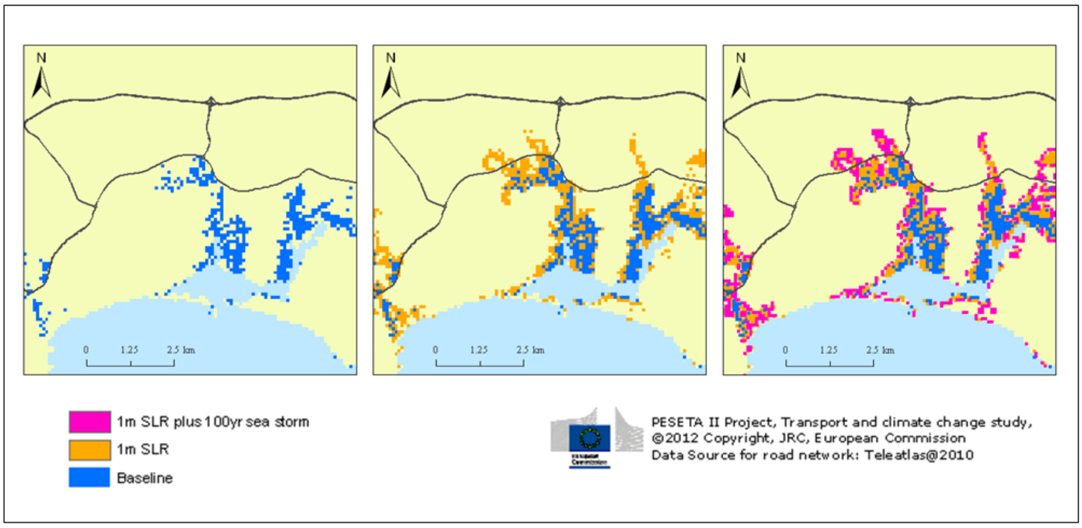

Figure 22: Areas at risk of permanent inundation currently (blue), and under a 1 m sea level rise (orange), and areas at risk of temporarily inundation (magenta)

Given these areas at risk of inundation, the affected transport network is inventoried. The road network at risk is presented (expressed in kilometers of road length) and in a percentage of the existing network within a 10 km coastal band. In total, under a 1 m sea level rise ~5400 km of roads in Europe (~4%) of the coastal road network (Table 30) would be at risk of permanent or temporary inundation. For low lying countries (Netherlands, Belgium, North Germany), much higher shares of coastal roads are projected to be at risk but, as explained earlier, these zones-related estimations are also the most inaccurate.

Considering a 6 million €/km average cost for motorway reconstruction (based on Cazala et al, 2006[29]), the total value of the asset at risk of permanent inundation due to a 1 m sea level rise is estimated to 18.5 billon €. This amount should be only interpreted as an indicator of vulnerability to sea level rise, in the case of a specific assumed 1 m SLR. It doesn't represent a damage costs or an adaptation costs as. As discussed previously, adaptation of transport should be considered as part of a broader multi-sectoral approach.

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[29] Conseil General des ponts et chassées, 2006, Rapport sur la comparaison au niveau european des coûts de construction, d'entretien et d'exploitation des routes

	Road infrastructure at risk of permanent or temporary inundation		
	km	% 10 km band	asset value (billon €)
AT	-	-	-
BE	218	18.7%	0.83
CZ	-	-	-
DE	705	12.2%	2.17
DK	163	2.2%	0.51
EE	1	0.1%	0.00
ES	156	0.8%	0.54
FI	-	-	-
FR	529	2.2%	1.65
GR	69	1.0%	0.27
HU	-	-	-
IE	17	0.6%	0.05
IT	1 412	12.5%	4.94
LT	382	54.3%	1.49
LU	-	-	-
LV	61	10.1%	0.21
NL	1 403	12.2%	4.79
PL	73	7.1%	0.20
PT	63	1.5%	0.24
RO	6	3.2%	0.02
SE	39	0.4%	0.15
SI	9	1.8%	0.03
SK	-	-	-
UK	124	0.5%	0.36
total	**5 430**	**4.1%**	**18.46**

Table 30: Road transport infrastructure at risk of permanent or temporary inundation in each country under a 1 m sea level rise and 100-yr sea storm surge

7.3 Concluding remarks

There is still a high uncertainty about the future seal level rise as it depends on the future emission trajectory and their effect on both thermal sea expansion and ice sheet melting. For the purpose of this analysis, one single sea level rise was considered for this analysis.

These results should be interpreted as initial estimates of future risk of sea level rise and sea storm surges on road transport infrastructure.
Both vulnerability and adaptation costs would need to be assessed under a much higher spatial resolution, more realistic method for simulating inundation processes. Due to these limitations, the assessed costs represent a very first element for risk analysis at EU-wide level but can't be interpreted as an adaptation cost.

Once a more detailed risk assessment is made, different adaptation measures can be investigated, some of them being applied specifically to transport infrastructure (e.g. infrastructure elevation, protection, or detour) others requiring a cross-cutting assessment including long term land use planning.

8 General discussion and conclusion

Transport systems could potentially be affected by a multitude of changes in the future climate, including hotter summer conditions, extreme precipitation events, increased storminess and sea level rise. This could accentuate infrastructure deterioration processes, risks of infrastructure failure and collapse, traffic disruption and, in the most severe cases, fatalities. Weather-induced traffic disruptions can also result in important consequences in supply chains and on the whole economy.

Construction design and maintenance of transport infrastructures are essential to maintain their integrity and serviceability. Nevertheless, complete avoidance of weather-induced infrastructure **deterioration and failures** is not economically feasible. Therefore, both average and extreme conditions represent a non negligible component into transport infrastructure costs.

For road transport infrastructures, weather stresses represent from 30% to 50% of current road maintenance costs in Europe (8 to 13 billon €/yr). About 10% of these costs (~0.9 billion €/yr) are associated with extreme weather events alone, in which extreme heavy rainfalls & floods events represent the first contribution.

Based on projected climate variables for Europe (E1, A1B, RCP8.5 scenarios) and relevant climate stressors, this research project has assessed future exposure of transport infrastructures (mainly roads and rail) to climate induced stressors and corresponding **trends about weather-induced deterioration and damages costs**.

8.1 Future impacts on road infrastructures

Based on projected climate variables for Europe (E1, A1B, RCP8.5 scenarios), this research project has assessed future exposure of transport infrastructures (mainly roads and rail) to climate induced stressors and corresponding **trends about weather-induced deterioration and damages costs**.

This study concludes that, at EU27 aggregated level, compared to today, average precipitation-induced degradation of road transport infrastructures will only slightly increase in the future. However, more frequent extreme precipitations and floods (river floods and pluvial floods) as expected in different regions in Europe could result in an extra cost for road transport infrastructures (50-192 million €/yr for the A1B scenarios, period 2040-2100). Milder winter conditions are projected to result in reduced costs for road infrastructure (-170 to -508 million €/yr for the A1B scenarios). On the contrary, increasing average temperature all over Europe could require changes in maintenance operations and practices and represent extra costs for both road transports.

These costs provide a highly aggregated overview of the possible trends for road transport in Europe. More severe consequences at local or regional level are not excluded, implying more significant additional spending to both repairing and maintenance of infrastructures, and, also, possible severe indirect consequences (e.g. fatalities due to extreme weather events). Current and future patterns about extreme precipitation for instance show a highly uneven distribution and future climate change may exacerbate such extreme events in some specific areas (e.g. Mediterranean countries).

8.2 Adaptation

A process-based approach, combining projected climate data with geographical transport information and technico-economic information, has been applied to assess future **vulnerability to heat stress, heavy rainfalls and sea level rise** (sea level rise) and **adaptation measures to mitigate risk for the two former stresses** (rail buckling risk, road pavement, bridge scour prevention).

Road Asphalt binder adaptation is the least costly measure and, given the relatively short life cycle (~7 years), it is not expected to represent a major challenge for infrastructure planner.

Protection of **river bridges** may be needed over the next decades for about 20% of the stock in order to mitigate scour risk associated with increasing river flood. Given that bridges are designed for long life spans (>100 years) and that their maintenance and repairing activities have to be planned long in advance, future climate-related risk should be included in corresponding prior cost-benefit studies. It has to be noted that in this study, only one particular climate scenario was considered, which may significantly underestimate the uncertainty about both the vulnerable bridge stock and adaptation costs.

Regarding heat-induced **rail buckling risk**, the most commonly applied adaptation measure (speed limits) results in trip delays. These were assessed to be currently negligible (~0.01% of total current trips time) and could be doubled or multiplied by four depending on the climate scenario (A1B or RCP8.5) over the period 2070-2100. Changing the track anchoring conditions (adapting stress-free temperature to higher summer temperatures) could help reducing these delays, but a detailed assessment would be needed to validate such an option and assess its costs.

The assessed costs are summarised in Table 31 and Table 32 the A1B scenario (million €/yr over the period 2040-2100).

For road infrastructures, the cost of the two adaptation measures are in total estimated to 314 to 560 million €/yr. Compared with maintenance costs, these estimated adaptation costs represent a small percentage (1.2% to 2.3%). Further assessment would however be needed to estimate avoided costs. For the case of bridge scour for instance, the cost associated with bridge failure could represent from 2 to 10 times the reconstruction costs.

	Current weather induced costs (million €/yr)		Change in future weather-induced costs (million €/yr)		Future cost for adaptation (million €/yr)		Total estimated costs (million €/yr)
	Weather-induced wear&tear	Extreme weather damage costs	Weather induced wear&tear (reduced winter deterioration)	Extreme weather damage costs	River bridges scour protection	Road pavement (asphalt binder)	
Alps	179	43	-6 - 0	3 - 11	16 - 19	3 - 4	16 - 34
UK & Ireland	2 213	59	-8 - -4	13 - 20	25 - 76	0 - 6	30 - 98
Eastern Europe	1 351	29	-44 - -4	3 - 9	29 - 39	16 - 61	5 - 105
France	535	133	-63 - -32	-4 - 29	34 - 73	6 - 15	-29 - 85
Iberia	369	86	-126 - -75	-2 - 5	41 - 45	10 - 15	-77 - -9
Mediterranea	4 038	53	-35 - -25	-2 - 3	52 - 57	9 - 11	23 - 47
Middle Europe	760	73	-201 - -27	13 - 37	27 - 32	9 - 57	-152 - 98
Scandinavia	959	153	-26 - -2	27 - 77	38 - 39	0 - 11	40 - 125
Total	**10 405**	**629**	**-508 - -170**	**50 - 192**	**262 - 381**	**52 - 180**	**-144 - 582**
% maintenance cost	*40.0%*	*2.4%*	*-2.0% - -0.7%*	*0.2% - 0.7%*	*1.0% - 1.5%*	*0.2% - 0.7%*	*-0.6% - 2.2%*

Table 31: Overview of current and future costs associated with impacts of climate change to road transport infrastructure and of costs of two adaptation measures (A1B scenario)

	Rail transport: adaptation costs (million €/yr)		
	River bridges	Rail track buckling	Total
Alps	4 - 5	1 - 1	5 - 6
UK & Ireland	6 - 19	0 - 1	7 - 20
Eastern Europe	7 - 10	4 - 6	11 - 16
France	8 - 18	4 - 5	12 - 23
Iberia	10 - 11	2 - 4	12 - 16
Mediterranea	13 - 14	6 - 13	19 - 27
Middle Europe	7 - 8	2 - 6	9 - 14
Scandinavia	10 - 10	1 - 2	10 - 12
Total	**66 - 95**	**25 - 48**	**90 - 143**

Table 32: Costs of two adaptation measures over the period 2040-2100 for rail infrastructures (A1B scenario)

Coastal infrastructure at risk due to sea level rise

This study has produced an initial estimate of future risk of sea level rise and sea storm surges on road transport infrastructure. This risk is mainly based on infrastructure settled in areas lying below a level defined by the sum of sea level rise (1 m) and 100-yr sea storm surge height. At European level, the so defined road infrastructure at risk of permanent represents 4.1% of the coastal infrastructure. The value of that infrastructure estimated to ~18.5 billion €.

8.3 Adaptation under high uncertainty

The above-mentioned geographically **uneven distribution of future impacts** and adaptation costs, combined with both uncertainty about future greenhouse gas emissions and significant variation across climate models, especially where extreme precipitations are concerned, represents an important challenge for infrastructure planner decision towards the most cost efficient adaptation strategy. For the case of transport infrastructure, this issue is particularly critical where long-live infrastructures are concerned (roads, bridges, sea ports…).

Also worth to note is the fact that, besides the climate projections themselves, important **data gaps and uncertainties** represent serious bottlenecks to provide high confidence cost estimates. These data gaps concern various aspects within the transport system (examples are infrastructure stock, including its size and geographical distribution, maintenance costs, current vulnerability and deficiency, traffic, current maintenance practices – e.g. stress free temperature for rail track). Statistics about transport infrastructure weather-induced damages are surprisingly missing for most parts of Europe, or at least not readily available.

The **uncertainty regarding climate data and climate model** projection is important, especially when using extreme values (e.g. precipitation). This is critical especially where further modeling process is applied to derive estimates on e.g. river floods, thus increasing the overall uncertainty.

The long life of transport infrastructures, combined with such uncertain future climate (over 20-100 years) makes the decision on adaptation strategy difficult. With this respect, two adaptation strategies could be envisaged:

- **Adaptive management** means that incremental adaptation is decided and implemented over successive short timescales (10 years for instance). The advantage is to manage climate change uncertainty iteratively, based on gradually increasingly reliable climate change, reducing the risk to commit to highly expensive investment which could tune out inadequate.
- **'One-off adaptation'** assumes that adaptation is undertaken once to deal with long-term.

The decision on such options and any other variants can only be made on real and concrete cases by incorporating the climate dimension in a cost-benefit.

The experience drawn from the four case studies in this research illustrates the need to apply engineering based bottom-up analysis. Assessing adaptation measures in the field of transport infrastructures intrinsically connects to highly specialised research fields and requires combination of expertise, knowledge and data in different fields (climate change, engineering, transport network, transport modelling, spatial information analysis, micro- and macro- economic analysis). Research and expert workshops consulted and/or attended in the course of this project have largely provided evidence that a comprehensive and reliable cost assessment of adaptation measures in the field of transport can hardly be conducted at a high scale (Europe) and where feasible, it has to be a **bottom-up engineering-based method** in which the physical mechanisms underlying the weather-induced consequences on infrastructures (e.g flow-bridge structure-sediment interactions inducing bridge scour) should be represented with adequate simplified equations.

Moderate, or even very low costs have been estimated in this study for the four case studies. More research and experience based evidence would be necessary to infer that the overall cost of adaptation for transport in general is limited. In any case, the climate dimension will need to be mainstreamed in future infrastructure planning and scheduled maintenance activities and data and methodological work will be needed to properly include that dimension in **cost-benefit analysis**. This may be the area on which further research should focus on in a next step.

With this respect, the need to make **transport infrastructure climate resilient** is explicitly added in the Transport White Paper as a condition to be fulfilled by future infrastructure projects: "*Co-funded projects should equally reflect the need for infrastructure that minimises the impact on the environment, that is resilient to the possible impact of climate change and that improves the safety and security of users*."

The question to be addressed is also whether **design codes** need to be revisited in the light of climate scenarios and projected consequences of e.g. river floods (see for instance the case of bridges).

Appendix I: Projected changes in temperatures by 2040-2070 and 2070-2100 for the A1B, E1 and RCP8.5 scenarios

	Average precipitation (extra mm/day by 2040-2070 compared with 1990-2010)								
	E1				A1B				RCP85
	E1-MPI-r1	E1-MPI-r2	E1-MPI-r2	average E2	A1B-DMI	A1B-KNMI	A1B-METO	average A1B	RCP8.5-DMI
AT	-7	49	13	18	43	40	3	29	73
BE	-10	25	-13	1	42	19	-48	4	2
BG	-50	11	-25	-22	-49	-44	-2	-32	1
CZ	9	24	16	16	43	58	-14	29	58
DE	-6	21	13	9	62	58	-31	30	46
DK	-12	-11	18	-2	62	17	14	31	8
EE	83	14	43	47	95	37	23	52	47
ES	-106	-44	-90	-80	-46	-81	-62	-63	-89
FI	73	-9	20	28	73	39	50	54	39
FR	-49	30	-9	-10	3	12	-93	-26	-31
GR	-56	-39	-77	-57	-113	-94	-68	-92	-48
HU	-41	21	-22	-14	10	-19	-16	-9	27
IE	72	78	63	71	-6	33	40	22	22
IT	-107	18	-73	-54	-41	-32	-50	-41	-55
LT	24	10	49	28	71	51	17	46	38
LU	-24	46	24	15	51	40	-48	15	14
LV	55	11	38	34	90	44	15	50	39
NL	-51	-14	-22	-29	58	10	-13	18	24
PL	8	6	20	11	52	34	0	29	33
PT	-146	-75	-146	-122	-54	-72	-75	-67	-128
RO	-46	24	-15	-13	-27	-9	10	-9	-7
SE	56	0	51	36	87	35	61	61	38
SI	-79	47	-71	-34	18	-12	-6	0	-26
SK	-31	25	-13	-6	16	9	-23	1	23
UK	33	41	26	33	37	20	31	29	14

	Average precipitation (extra mm/day by 2070-2100 compared with 1990-2010)								
	E1				**A1B**				**RCP85**
	E1-MPI-r1	**E1-MPI-r2**	**E1-MPI-r2**	**average E2**	**A1B-DMI**	**A1B-KNMI**	**A1B-METO**	**average A1B**	**RCP8.5-DMI**
AT	-18	18	27	9	36	58	0	31	73
BE	-54	23	-10	-14	73	79	-62	30	-19
BG	-58	-28	-62	-49	-62	-90	-36	-62	-13
CZ	-5	9	11	5	52	74	4	43	60
DE	-21	19	-5	-3	88	97	-17	56	39
DK	16	27	48	30	104	35	3	47	-7
EE	73	24	62	53	131	62	8	67	53
ES	-94	-99	-117	-103	-81	-168	-54	-101	-136
FI	70	14	51	45	152	84	74	103	88
FR	-82	-6	-42	-43	43	35	-63	5	-85
GR	-101	-115	-157	-124	-167	-130	-90	-129	-87
HU	-26	-26	-27	-26	-14	-14	-24	-17	12
IE	70	133	35	79	77	119	62	86	-21
IT	-121	-95	-117	-111	-69	-100	-34	-68	-85
LT	60	19	57	45	94	44	23	54	29
LU	-11	49	41	26	110	102	-57	51	12
LV	64	9	54	42	114	50	5	57	33
NL	-64	-1	-27	-31	108	74	-40	47	20
PL	13	15	8	12	49	33	3	28	31
PT	-133	-120	-166	-139	-138	-204	-62	-135	-200
RO	-55	-22	-44	-40	-33	-36	-27	-32	-9
SE	72	23	61	52	157	79	89	108	81
SI	-90	-92	-87	-89	-13	-74	-31	-39	-35
SK	-9	-18	-10	-12	1	1	-29	-9	16
UK	27	65	29	41	102	82	36	73	-1

	Average precipitation (extra mm/day compared with 1990-2010)								
	E1				**A1B**				**RCP85**
	E1-MPI-r1	**E1-MPI-r2**	**E1-MPI-r2**	**average E2**	**A1B-DMI**	**A1B-KNMI**	**A1B-METO**	**average A1B**	**RCP8.5-DMI**
AT	-18	18	27	9	36	58	0	31	73
BE	-54	23	-10	-14	73	79	-62	30	-19
BG	-58	-28	-62	-49	-62	-90	-36	-62	-13
CZ	-68	-18	-60	-49	52	74	4	43	-74
DE	-5	9	11	5	88	97	-17	56	60
DK	-21	19	-5	-3	104	35	3	47	39
EE	16	27	48	30	131	62	8	67	-7
ES	73	24	62	53	-81	-168	-54	-101	53
FI	-94	-99	-117	-103	152	84	74	103	-136
FR	70	14	51	45	43	35	-63	5	88
GR	-82	-6	-42	-43	-167	-130	-90	-129	-85
HU	-101	-115	-157	-124	-14	-14	-24	-17	-87
IE	-26	-26	-27	-26	77	119	62	86	12
IT	70	133	35	79	-69	-100	-34	-68	-21
LT	-121	-95	-117	-111	94	44	23	54	-85
LU	60	19	57	45	110	102	-57	51	29
LV	-11	49	41	26	114	50	5	57	12
NL	64	9	54	42	108	74	-40	47	33
PL	-64	-1	-27	-31	49	33	3	28	20
PT	13	15	8	12	-138	-204	-62	-135	31
RO	-133	-120	-166	-139	-33	-36	-27	-32	-200
SE	-55	-22	-44	-40	157	79	89	108	-9
SI	72	23	61	52	-13	-74	-31	-39	81
SK	-90	-92	-87	-89	1	1	-29	-9	-35
UK	-9	-18	-10	-12	102	82	36	73	16

	Tmax_7day by 2040-2070 (difference in centigrade with 1990-2010)								
	E1				A1B				RCP85
	E1-MPI-r1	E1-MPI-r2	E1-MPI-r2	average E2	A1B-DMI	A1B-KNMI	A1B-METO	average A1B	RCP8.5-DMI
AT	1.5	1.8	0.3	1.2	0.9	2.5	2.2	1.9	1.5
BE	-0.3	2.0	1.0	0.9	0.5	1.1	2.1	1.2	1.9
BG	2.5	0.5	2.1	1.7	1.3	1.5	1.7	1.5	1.5
CZ	1.5	1.3	0.1	1.0	0.0	1.3	2.0	1.1	1.1
DE	0.6	1.8	0.8	1.0	0.4	2.2	2.5	1.7	1.4
DK	1.3	2.2	1.3	1.6	0.2	2.7	1.8	1.6	1.0
EE	2.4	0.5	1.3	1.4	2.1	3.9	1.5	2.5	-0.2
ES	1.4	1.5	1.7	1.5	2.0	2.7	3.0	2.6	1.9
FI	2.8	0.4	2.0	1.7	2.6	3.6	3.9	3.4	0.0
FR	0.4	1.9	1.3	1.2	1.2	1.5	2.4	1.7	1.8
GR	2.4	0.8	2.6	1.9	1.8	2.1	1.9	1.9	1.9
HU	1.9	1.2	-0.2	0.9	-0.1	1.3	1.0	0.7	1.1
IE	0.2	2.1	1.3	1.2	1.0	1.7	1.7	1.5	1.5
IT	1.6	1.3	1.4	1.4	1.5	2.7	1.9	2.1	1.6
LT	1.4	0.6	0.4	0.8	1.2	3.3	1.6	2.0	0.4
LU	0.0	1.7	1.1	0.9	0.3	1.5	2.3	1.4	1.9
LV	2.0	0.5	0.7	1.0	1.5	3.3	1.4	2.0	0.0
NL	-0.4	1.8	0.8	0.7	0.5	1.8	1.5	1.3	1.6
PL	1.3	0.9	0.2	0.8	0.4	1.7	2.0	1.4	0.8
PT	1.3	1.1	1.4	1.3	1.5	2.0	2.3	1.9	1.6
RO	2.0	0.6	0.8	1.1	0.7	1.1	1.8	1.2	1.3
SE	2.2	1.5	1.4	1.7	1.6	3.2	3.1	2.7	0.7
SI	2.0	1.6	0.4	1.4	0.8	2.6	1.6	1.6	1.7
SK	1.6	1.1	-0.5	0.8	0.0	1.3	1.6	1.0	0.4
UK	0.2	2.3	1.2	1.2	1.2	1.0	1.4	1.2	0.8

	Tmax_7day by 2070-2100 (difference in centigrade with 1990-2010)								
	E1				**A1B**				**RCP85**
	E1-MPI-r1	**E1-MPI-r2**	**E1-MPI-r2**	**average E2**	**A1B-DMI**	**A1B-KNMI**	**A1B-METO**	**average A1B**	**RCP8.5-DMI**
AT	2.1	1.6	0.7	1.5	1.8	3.9	3.4	3.0	3.5
BE	1.0	1.7	2.0	1.6	1.2	5.3	2.3	2.9	3.7
BG	2.7	1.9	2.4	2.4	2.3	3.1	3.5	3.0	3.7
CZ	1.9	1.2	0.8	1.3	1.2	3.3	3.4	2.6	3.5
DE	1.4	1.4	1.8	1.5	1.6	4.9	3.6	3.4	3.9
DK	1.4	1.4	2.4	1.7	1.1	3.9	3.6	2.9	3.3
EE	1.8	0.2	2.1	1.4	1.7	3.4	4.9	3.3	2.1
ES	2.1	1.8	2.6	2.2	4.4	4.7	4.1	4.4	4.4
FI	1.7	0.2	2.6	1.5	1.9	3.9	6.3	4.0	2.3
FR	1.5	1.9	2.1	1.8	2.8	4.5	2.5	3.3	4.4
GR	2.9	2.3	3.0	2.8	2.9	3.7	3.4	3.3	4.1
HU	2.3	1.7	0.5	1.5	1.1	2.9	3.9	2.6	3.4
IE	0.4	1.5	1.6	1.2	0.5	2.3	3.5	2.1	4.3
IT	2.5	2.0	2.1	2.2	2.8	4.4	2.5	3.3	4.1
LT	1.3	0.2	1.3	1.0	1.7	3.1	3.5	2.7	2.6
LU	1.3	1.6	2.0	1.6	1.6	6.1	2.4	3.4	4.2
LV	1.5	0.1	1.6	1.1	1.7	2.8	4.0	2.8	2.2
NL	0.7	1.4	1.8	1.3	1.3	4.6	2.5	2.8	3.5
PL	1.5	0.8	1.1	1.1	1.4	2.7	3.4	2.5	3.1
PT	1.7	1.0	2.4	1.7	3.3	4.1	3.7	3.7	4.0
RO	2.3	1.7	1.3	1.7	1.6	2.6	4.0	2.7	3.2
SE	1.5	1.1	2.3	1.6	1.4	3.9	4.4	3.2	3.2
SI	2.7	1.9	1.2	2.0	1.4	4.1	3.4	3.0	4.0
SK	1.9	1.5	0.3	1.2	1.1	3.0	4.0	2.7	3.4
UK	0.7	1.9	1.9	1.5	1.2	1.9	3.2	2.1	3.6

	Freezing-Day index by 2040-2070 (% decrease compared with 1990-2010)								
	E1				**A1B**				**RCP85**
	E1-MPI-r1	**E1-MPI-r2**	**E1-MPI-r2**	**average E2**	**A1B-DMI**	**A1B-KNMI**	**A1B-METO**	**average A1B**	**RCP8.5-DMI**
AT	-37%	-37%	-48%	-41%	-54%	-52%	-66%	-57%	-60%
BE	-51%	-44%	-69%	-55%	-80%	-78%	-79%	-79%	-82%
BG	-47%	-21%	-53%	-40%	-60%	-60%	-68%	-63%	-66%
DE	-52%	-43%	-63%	-53%	-74%	-69%	-76%	-73%	-72%
DE	-56%	-47%	-69%	-57%	-74%	-69%	-76%	-73%	-76%
DK	-71%	-58%	-85%	-71%	-80%	-75%	-86%	-80%	-85%
EE	-58%	-47%	-62%	-56%	-60%	-57%	-69%	-62%	-68%
ES	-47%	-62%	-68%	-59%	-84%	-78%	-86%	-82%	-87%
FI	-46%	-40%	-52%	-46%	-55%	-52%	-61%	-56%	-65%
FR	-43%	-50%	-59%	-51%	-77%	-76%	-78%	-77%	-76%
GR	-57%	-35%	-61%	-51%	-75%	-74%	-81%	-76%	-74%
HU	-52%	-41%	-64%	-53%	-65%	-64%	-76%	-69%	-75%
IE	-74%	-42%	-83%	-67%	-89%	-92%	-92%	-91%	-98%
IT	-46%	-43%	-54%	-47%	-59%	-58%	-69%	-62%	-64%
LT	-53%	-44%	-63%	-53%	-60%	-54%	-68%	-60%	-69%
LU	-50%	-46%	-68%	-55%	-79%	-74%	-78%	-77%	-79%
LV	-54%	-45%	-63%	-54%	-60%	-56%	-68%	-62%	-69%
NL	-64%	-43%	-78%	-62%	-81%	-78%	-78%	-79%	-81%
PL	-57%	-45%	-69%	-57%	-65%	-59%	-71%	-65%	-74%
PT	32%	-75%	-94%	-46%	-99%	-98%	-97%	-98%	-100%
RO	-44%	-30%	-53%	-42%	-53%	-54%	-65%	-57%	-62%
SE	-45%	-37%	-51%	-44%	-54%	-48%	-60%	-54%	-62%
SI	-40%	-37%	-56%	-44%	-64%	-61%	-72%	-66%	-70%
SK	-50%	-41%	-63%	-51%	-59%	-60%	-72%	-64%	-71%
UK	-64%	-49%	-76%	-63%	-88%	-86%	-91%	-88%	-93%

	Freezing-Day index by 2070-2100 (% decrease compared with 1990-2010)								
	E1				A1B				RCP85
	E1-MPI-r1	**E1-MPI-r2**	**E1-MPI-r2**	**average E2**	**A1B-DMI**	**A1B-KNMI**	**A1B-METO**	**average A1B**	**RCP8.5-DMI**
AT	-37%	-37%	-48%	-41%	-54%	-52%	-66%	-57%	-60%
BE	-51%	-44%	-69%	-55%	-80%	-78%	-79%	-79%	-82%
BG	-47%	-21%	-53%	-40%	-60%	-60%	-68%	-63%	-66%
CZ	-52%	-43%	-63%	-53%	-65%	-61%	-74%	-67%	-72%
DE	-56%	-47%	-69%	-57%	-74%	-69%	-76%	-73%	-76%
DK	-71%	-58%	-85%	-71%	-80%	-75%	-86%	-80%	-85%
EE	-58%	-47%	-62%	-56%	-60%	-57%	-69%	-62%	-68%
ES	-47%	-62%	-68%	-59%	-84%	-78%	-86%	-82%	-87%
FI	-46%	-40%	-52%	-46%	-55%	-52%	-61%	-56%	-65%
FR	-43%	-50%	-59%	-51%	-77%	-76%	-78%	-77%	-76%
GR	-57%	-35%	-61%	-51%	-75%	-74%	-81%	-76%	-74%
HU	-52%	-41%	-64%	-53%	-65%	-64%	-76%	-69%	-75%
IE	-74%	-42%	-83%	-67%	-89%	-92%	-92%	-91%	-98%
IT	-46%	-43%	-54%	-47%	-59%	-58%	-69%	-62%	-64%
LT	-53%	-44%	-63%	-53%	-60%	-54%	-68%	-60%	-69%
LU	-50%	-46%	-68%	-55%	-79%	-74%	-78%	-77%	-79%
LV	-54%	-45%	-63%	-54%	-60%	-56%	-68%	-62%	-69%
NL	-64%	-43%	-78%	-62%	-81%	-78%	-78%	-79%	-81%
PL	-57%	-45%	-69%	-57%	-65%	-59%	-71%	-65%	-74%
PT	32%	-75%	-94%	-46%	-99%	-98%	-97%	-98%	-100%
RO	-44%	-30%	-53%	-42%	-53%	-54%	-65%	-57%	-62%
SE	-45%	-37%	-51%	-44%	-54%	-48%	-60%	-54%	-62%
SI	-40%	-37%	-56%	-44%	-64%	-61%	-72%	-66%	-70%
SK	-50%	-41%	-63%	-51%	-59%	-60%	-72%	-64%	-71%
UK	-64%	-49%	-76%	-63%	-88%	-86%	-91%	-88%	-93%

Appendix II: Projected changes precipitation by 2040-2070 and by 2070-2100 for the A1B, E1 and RCP8.5 scenarios

	average			**MPI-E1-r1**			**MPI-E1-r2**		
2040-2070	pavg	p50	pmax_7day	pavg	p50	pmax_7day	pavg	p50	pmax_7day
Alpines Regions	1%	6%	-1%	5%	24%	0%	0%	-3%	1%
UK & Ireland	4%	37%	6%	5%	12%	9%	3%	49%	6%
Eastern Europe	-1%	19%	-2%	3%	6%	-2%	0%	10%	-2%
France	-1%	8%	5%	4%	13%	10%	-1%	10%	8%
Iberian Peninsula	-13%	-7%	-6%	-7%	0%	1%	-14%	-7%	-7%
Mediterranea	-7%	-1%	-5%	0%	15%	-1%	-10%	-9%	-8%
Middle Europe	1%	22%	1%	2%	75%	1%	1%	-47%	-3%
Scandinavia	5%	125%	7%	0%	84%	-1%	7%	96%	10%

	average			**MPI-E1-r1**			**MPI-E1-r2**		
2070-2100	pavg	p50	pmax_7day	pavg	p50	pmax_7day	pavg	p50	pmax_7day
Alpines Regions	-1%	10%	1%	0%	9%	0%	0%	-6%	3%
UK & Ireland	5%	45%	5%	8%	8%	4%	3%	27%	7%
Eastern Europe	-3%	31%	-2%	-1%	17%	-4%	-4%	17%	-2%
France	-5%	-8%	0%	-1%	-21%	-1%	-5%	2%	5%
Iberian Peninsula	-16%	-13%	-6%	-15%	-8%	-4%	-18%	-8%	-5%
Mediterranea	-15%	-18%	-10%	-13%	-17%	-8%	-18%	-18%	-10%
Middle Europe	-1%	15%	-1%	2%	22%	-1%	-1%	-18%	-5%
Scandinavia	8%	94%	5%	3%	70%	-1%	10%	72%	8%

Table 33: Change in precipitation regime by 2040-2070 and 2070-2100 as percentage of current situation for the 3 E1 scenarios (pavg: average annual precipitation; p50: number of days with precipitation > 50 mm; pmax_7day: average of the annual maximum precipitation over consecutive days)

	DMI-RCP8.5		
	pavg	p50	pmax_7day
Alpines Regions	5%	53%	6%
Bristish Isles	1%	43%	6%
Eastern Europe	4%	64%	4%
France	-4%	29%	6%
Iberian Peninsula	-15%	-7%	5%
Mediterranea	-8%	16%	6%
Middle Europe	5%	77%	5%
Scandinavia	7%	85%	2%

	DMI-RCP8.5		
	pavg	p50	pmax_7day
Alpines Regions	5%	91%	14%
Bristish Isles	-1%	95%	16%
Eastern Europe	3%	85%	11%
France	-10%	35%	15%
Iberian Peninsula	-23%	-2%	13%
Mediterranea	-12%	16%	13%
Middle Europe	4%	134%	14%
Scandinavia	13%	251%	11%

Table 34: Change in precipitation regime and change in winter condition) by 2040-2070 and 2070-2100 as percentage of current situation for the RCP8.5 scenarios (pavg: average annual precipitation; p50: number of days with precipitation > 50 mm/day; pmax_7day: average of the annual maximum precipitation over consecutive days

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Abstract

This report provides a general EU-wide outlook about the future vulnerability of transport to climate change with a focus on the road and rail transport and their infrastructures. It also analyses some specific adaptations measures, illustrating key issues to be considered for policy making. It represents a first JRC/IPTS scientific contribution to the analysis of future impacts of climate change on the transport system in Europe, and has been conducted in the framework of the JRC PESETAII project.

Depending on future global warming and the region in Europe, transport modes and system components could be affected by one or several simultaneous changes in the climate conditions, including hotter summer conditions, extreme precipitation events, increased storminess and sea level rise. If such impacts are not anticipated in future transport infrastructure design and maintenance, those changing weather conditions could, in some regions, accelerate their deterioration, increase severe damages risks, traffic interruption and accidents which could, on their turn, affect economic activities.

This research project has drawn some future trends regarding changing exposure of road and rail infrastructures to weather-induced risk under climate change, considering two future time intervals (2040-2070 and 2070-2100), future infrastructure deterioration and damage costs and costs associated with some selected adaptation cases.

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