

Large and small numbers: options for quantifying the costs of extremes on transport now and in 40 years

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Abstract The past 15 years has been characterized by a high density of record-breaking weather extremes in Europe. These include the extratropical cyclones Lothar, Kyrill and Xynthia across western and mid Europe; the major floods in the UK, Germany and eastern Europe; the heat waves in 2003 and 2007 and, after a long period of mild winters, the heavy winter seasons in 2009/2010 and 2010/2011. Inspired by the rising trends in weather-related damages worldwide and the studies on the topic carried out in overseas, the EC funded the sister projects such as Weather Extremes-Assessing the Impacts on Transport and Hazards for European Regions (WEATHER), EWENT and ECCONET to determine the magnitude of current and future risks to the European transport sector and to assess suitable adaptation strategies. This paper presents the assessment framework of the WEATHER project and the results of weather-inflicted damage costs now and in 2040–2050. Total annual damages are found to be around €2.5 billion, which largely attribute to road traffic. However, broken down to passenger and ton kilometers the highest risk is borne by rail traffic due to its expensive infrastructures and its comparably complex operating structure. This indication even amplifies when looking four decades ahead: while average road transport costs will only raise by 7 % due to milder winters, rail traffic costs may increase by up to 80 % due to more floods and less predictable winter periods. A comparison with the results of the EWENT study uncovers a high range of uncertainty

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concerning methodological approaches and data treatment. Thus, the final figures might even be much higher.

Keywords Transport · Weather extremes · Climate change · Cost assessment · Risk · Forecast

1 Introduction

1.1 Background and motivation

The past 15 years has been characterized by a high density of record-breaking weather extremes in Europe. In 1999, 2007 and 2010, the extratropical cyclones such as Lothar, Kyrill and Xynthia damaged wide areas of France and Germany, and in 2002, 2005, 2006, 2010 as well as in 2013 major floods affected Germany, Poland, the Czech Republic, Bulgaria and their neighbor countries. The heat waves in 2003 and 2007 caused major wildfires with considerable problems for settlements, human health and transportation, and after a long period of mild winters the cold spells and snow storms 2009/2010 and 2010/2011 challenged all transport modes and public services. These events are recorded and assessed by several sources, e.g., by analysts of the big reinsurance companies (Munich 2011) or emergency management database (EM-DAT) of the Leuven University (Guha-Sapir et al. 2012). According to the EM-DAT database, 400 extreme meteorological and hydrological events within the decade 1999–2008 were counted killing 77,371 people and costing 113.6 billion euros. Related to the roughly 500 million inhabitants of Europe, this is about 23 Euros of damage costs per person and year.

The datasets of EM-DAT (Guha-Sapir et al. 2012), Munich (2011) or the European Severe Storms Laboratory (ESSL 2011) clearly show rising trends and frequency, intensity and entailed costs of weather extremes in Europe as well as all over the world. According to Munich 2011, the most costly year ever in terms of damages was caused by natural hazards. And if we disregard the dramatic consequences of the Fukushima catastrophe, this negative record is held by the year 2010 (Munich 2010). On the regional scale, however, in 2011, Europe was hit by fewer and less severe natural disasters than on average during the past decade.

The causes of this trend are manifold. In the past century, and in particular in the recent decades, accumulated values of the built environment have increased, building standards have become more risky in most parts of the world, the migration trend toward big coastal cities is persistent and observation and reporting techniques of damages have substantially improved (World Bank 2010). If prevention will not significantly improve, the estimated global damages toward the end of the century may increase to 134 billion Euros, which is three times today's level.

A recent study on the topic by Munich (2012) reveals that, even when correcting for these manmade risk increases, a clear trend for rising impacts of natural hazards can be read out of statistical data, which may give evidence to the first measurable footprint of climate change on human societies. Among all world regions as indicated by re-insurance statistics and the WEATHER international panel reports (Doll et al. 2011), the most significant raise in damages has been observed in the United States. Geologically, this can be explained by the absence of a mountain range running from east to west, separating hot from cold air. In North America, natural hazards have been rising by five times in the past

three decades, compared to a raise by four in Asia, 2.5 in Africa, two in Europe and 1.5 in South America.

Following the IPCC 4th Assessment Report (IPCC 2007), human impact on the increasing number and severity of extreme weather events is almost certain. For instance, Stott et al. (2004) found that anthropogenic greenhouse gas (GHG) emissions into the atmosphere have doubled the risk of that heave with a confidence of 90 %. The dry spells and heat waves in Australia in 2009 and 2012 and elsewhere in the world support this assumption. However, as the earth climate is subject to strong short- to long-term temperature cycles and as we do not have a comparative world without human GHG emissions at hand, human responsibility for the changing earth climate and entailed meteorological activities can only be simulated using complex computer models (Allen 2009).

Based on multiple climate models, the IPCC 4th Assessment Report (IPCC 2007) arrived at the conclusion that frequency and severity of extremes will significantly increase, in particular toward the end of this century. Highest impacts are expected for those countries suffering already from excessive floods, storms, heat and water stress, namely the poorer parts of the planet. But also for Europe, were climate conditions are today, and will most likely remain, very temperate compared to other world regions, changes will get visible. These will hit all sectors with the highest impacts expected on agriculture and coastal areas.

In its 2013 global risk map, the World Economic Forum (Howell 2013) places the failure of climate change adaptation and rising GHG emissions within the group of risks with the highest likelihood to occur in the next 10 years and the highest potential impact. However, World Bank (2010) conclude that prevention measures are not necessarily expensive: information of citizens and better maintenance of infrastructures at risk could be carried out with little additional costs. This general statement can be confirmed for the transport sector by reviewing the European and worldwide case studies carried out by the WEATHER project and its international panel members (Doll et al. 2012). Across 14 international cases of natural hazards, it could be shown that good preparedness does not necessarily require high volumes of investments, but is capable of reducing the consequences of extremes to a minimum.

Although not on the top position of suffering sectors, the European transport sector is already now affected by adverse weather conditions and will be so even more in the future. As an intermediate sector, transport then will affect other parts of the economy and of social life. The high interconnection between different transport networks on the one hand and between transport and other economic sectors on the other hand on a continental and global scale calls for a joined multiregional and multisectoral endeavor to mitigate future risks. While industries such as road logistics and shipping prefer not to think about adaptation options now, the railways (Nolte et al. 2011; UIC 2010) and aviation (EU-ROCONTROL 2011a) started to explore upcoming risks and appropriate coping strategies.

1.2 Objectives and structure

According to the World Bank report on “Natural Hazards and UnNatural Disasters” (World Bank 2010), sound adaptation strategies are capable of mitigating the most extreme consequences of weather extremes and climate change. Although in general benefits outweigh costs of disaster preparedness by a factor 15, the establishment of preparedness plans, cooperation strategies and communication concepts requires staff resources and the breaking open of established routines and traditions. Initiating processes of awareness and

strategy building at company and agency levels thus requires as sound as possible information on their potential costs and benefits.

The benefit side of adaptation strategies includes the direct potential to mitigate the risks of climate change and weather events for the agent implementing them and possibly for third parties, as well as secondary benefits. The latter could, for instance, be an increased reliability of services under all conditions through the modernization of information and communication systems for better preparedness. The assessment of the benefits from climate adaptation thus can become very broad and thus exceeds the scope of this paper. Here, we concentrate on the risk side of weather extremes on the European transport sector.

With this paper, we take a look into the future of the exposure of European transport systems to the consequences of climate change and weather extremes. We will tackle two questions: Which are the main drivers of weather-related costs of road, rail and air transport? How will they most likely develop and how big are the uncertainties of their development? The analysis is built on the results of the recently finalized research project WEATHER (Weather Extremes-Assessing the Impacts on Transport and Hazards for European Regions) funded under the 7th RTD framework program of the European Commission. The objectives of the project included to get a first idea of the level of economic costs caused by extreme weather conditions. Due to the broadness of the WEATHER research, including emergency management, adaptation strategies, case studies and policy issues, the task of cost estimation was restricted to only one scenario for indices of extremes and for the development of the transport sector. Ideally, a minimum of nine scenarios looking at upper and lower pathways for meteorological and transport sector indicators could be considered.

We leave these and other details open to further research. However, in order to get an idea of possible uncertainty ranges, the findings of the sister project EWENT funded under the same call of the EC are discussed in this paper. By looking into the methodological approaches and the results obtained by the two studies, common messages shall be identified, alternative assessment approaches shall be discussed and open research questions shall be uncovered.

Although several joined activities have been carried out by the WEATHER and the EWENT project, this paper is the first attempt to analyze and interpret our methods and results. The findings will form a fundamental pillar of the follow-up research study MOWE-IT embracing the core partners of WEATHER and EWENT and started in October 2012. With this work, we hope to contribute to a common understanding of the economics of extremes by relevant decision bodies, which will certainly be of increasing significance in the decades to come.

Section 2 provides an overview of existing studies on the costs of extremes on transport systems as well as on the economy in general. These numbers shall enable us to set the cost estimates of the WEATHER and EWENT project into relation to rather specific damages on the local level as well as to cross-sector damage estimates on national or international level.

Section 3 then looks into the cost estimation methodology developed by the EC-funded project WEATHER. The critical issues of appropriate data sources, assessment principles and the definition of extremes are discussed by mode of transport and hazard category.

Section 4 presents the results of the damage estimates for the period 1998–2010 and the forecasts to 2040–2050 by European climate regions. While the WEATHER methodology separates between transport modes, this section discusses the special case of intermodal freight transport. Finally, Sect. 5 closes the paper with a comparison of the WEATHER

results to the parallel study EWENT and draws together the findings of the previous sections for policy and research recommendations.

2 Evidence on the costs of weather extremes to transport

2.1 Roads and road travel

Before the European Commission has launched the sister studies WEATHER and EWENT, the majority of work on the impacts of climate change and weather extremes on transport systems had been conducted in the USA, Australia and New Zealand, while European research was rather fragmented.

TRB (2008) find for North American road assets that the share of maintenance and renewal costs attributable to weather extremes varies from 10 to 72 % of total maintenance and repair costs, which is due to the different climatic conditions and road types. Damages are caused by precipitation and floods, storms, winter conditions or a combination of them. The US Federal Highway Administration estimates the repair costs on its network caused by snow and ice at US \$5 billion annually. European studies suggest that one of the most severe weather conditions causing damages to transport networks is extensive flooding. For instance, the total cost to return the English road network back to its prior condition after the floods in December 2009/January 2010 and March 2010 was accounted at US \$6.019 million,¹ which is US \$9,188 per kilometer. The effects of strong winds are rarely researched. However, some evidence from the hurricane Katrina in New Orleans in 2005 might be used as exemplary evidence.

2.1.1 Network operations

Winter maintenance is an essential cost component of infrastructure management and operations. Norway spends roughly 30 % of its maintenance budget for winter maintenance; Slovenia reports a share of 50 %; and in Switzerland these costs can amount to 15–25 % of total annual maintenance costs (PIARC 2010). The high importance of maintenance activities for preparing transport networks for disaster risks and for re-establishing their functionality during and after an adverse event is emphasized by an international review of the World Bank (Muzira et al. 2010).

The most immediate impact of more intense precipitation will be increased flooding of coastal roads. Low-lying bridge and tunnel entrances for roads, rail, and rail transit will also be more susceptible to flooding, and thousands of culverts could be undersized for flows. Engineers must be prepared to deal with the resulting erosion and subsidence of road bases and rail beds, as well as erosion and scouring of bridge supports. Interruption of road traffic is likely to become more common with more frequent flooding. When precipitation falls as rain rather than snow, it leads to immediate runoff and increases the risk of floods, landslides, slope failures and consequent damage to roadways, especially rural roadways in the winter and spring months.

Warming winter temperatures will lead to reduced snow and ice removal costs, lessen adverse environmental impacts from the use of salt and chemicals on roads and bridges, extend the construction season, and improve the mobility and safety of passenger and freight travel through reduced winter hazards. Expected increases in temperature extremes,

¹ Converted with the exchange rate of 10/10/2012 of 1.608 US \$/GBP.

however, will have less positive impacts. More freeze–thaw conditions may occur, creating frost heaves and potholes on road and bridge surfaces and resulting in load restrictions on certain roads to minimize the damage. With the expected earlier onset of seasonal warming, the period of springtime load restrictions may be reduced in some areas but is likely to expand in others with shorter winters but longer thaw periods. Excessive summer heat spells are likely to increase the risk of wildfires, threatening communities and infrastructure directly and bringing about road and rail closures in affected areas. Longer periods of extreme heat may compromise pavement integrity (e.g., softening asphalt and increasing rutting from traffic) and cause thermal expansion of bridge joints, adversely affecting bridge operation and increasing maintenance costs.

2.1.2 Accidents

The causal relation between adverse weather and accident rates is not always clear. Even though research has shown that motorists adjust their driving behavior during bad weather, there is overwhelming evidence that accident risks increase during rains and snow. Research in the Netherlands gives clear indications that precipitation and temperature are the most important factors, when examining the relationship of weather and road safety in both summer and winter (Bos 2001). A great amount of precipitation, as either rain or snow, generally accompanies a higher victim rate for all modes of transport as then the friction of the road surface goes down significantly. Based on a literature review by Bijleveld and Churchill (2009), one can assume that the crash rate approximately doubles during rain. However, Yannis and Karlaftis (2010) contradict these results by finding for Athens that in rainy conditions accident number and fatalities both for cars and pedestrians decline significantly due to more cautious driving. Drivers travel much slower when faced with winter weather, compared to rainy weather. However, ice on Dutch National State Roads increases the number of accidents of between 77 and 245 % (Stiers 2005). Other studies confirm this trend: Hermans et al. (2005) for Belgium and Knapp et al. (2000), Qiu (2007), Perry and Symons (1991) and Maze et al. (2005).

2.1.3 Time losses

As concerns weather-inflicted delays, the US Federal Highway Administration concludes that rain causes wet pavement, which reduces vehicle traction, maneuverability, visibility distance and thereby prompts drivers to travel at lower speeds causing reduced roadway capacity and increased delay. Various studies in the USA reveal traffic flow reductions due to winter conditions. The flow reductions range between 7 and 56 % and speed reductions between 3 and 40 %. Research in Europe observes reduced traffic speeds by 7 % in the Netherlands and capacity reduction by 10–60 % during snowfall on German motorways. Research in the Netherlands reveals that strong winds reduce traffic speed by about 3 % on average. During rains car speeds are found to drop by 2–17 % according to several studies in the USA.

2.2 Railway networks

Although the majority of literature on climate change impacts on transport deals with the road sector, there is an emerging number of works at governmental and association level devoted to railways. The growing attention for the railways has manifold reasons. First,

infrastructures are more expensive and more difficult to restore compared to road, aviation or shipping facilities. Second, train operations are more prone to disruptions and user are supposed to be less willing to accept delay and cancellations of services.

With the project ARISCC (Adapting Railway Infrastructure to Climate Change), the International Union of Railways (UIC) has recently carried out a comprehensive review of weather- and climate-related risks and problems and assembled good practice in incident management and weather data provision of railway undertakings across Europe (Nolte et al. 2011). The study concludes that a standardized recording and assessment of incidents, the provision of precise weather information to the relevant entities inside the railway organizations, awareness raising by regular information and communication and good maintenance practices are in most cases much more efficient than investments in expensive infrastructure protection measures. The present resilience of the railways could prove to be insufficient to cope with higher temperatures, more frequent heat waves and a higher number of permanent as well as convective rainfalls. Short-, mid- and long-term adaptation strategies should follow the three “R” principle: readiness, resilience and recovery.

A closer look into winter problems of the railways is taken by a second study commissioned by UIC: Winter and Railways (UIC 2010). By consultation of winter problems in the past decades, the study not only identifies frozen or snow-packed switches and white ice on pantographs a major problem, but also states that good solutions not always need to be technical. This holds in particular true in case of non frequent occurrences, such as ice in doors. Winter problems cannot be solved by one universal solution. The most critical issues for getting through extreme winters are the mobilization, financing and training of staff and the availability of locomotives and snow clearance equipment.

The latest review of high summer temperatures due to climate change on buckling and rail-related delays in the south-east Kingdom is provided by the FUTURE-NET project (Dobney et al. 2009). Estimates have shown that 20 % of all unplanned delays on the UK rail network are the cause of present-day adverse weather conditions. Due to climate change, weather-related problems such as buckling, flooding due to inadequate drainage, sudden earthworks failure, scour at the base of bridges and damage to overhead wires will occur with increasing frequency on the network.

On the contrary, high summer temperatures may cause buckling of rail tracks and may challenge air conditioning in coaches. A buckle is any track misalignment serious enough to cause a derailment (Enei et al. 2011). Although railway track is pre-stressed to withstand a reasonable temperature range, extremes of temperatures can cause both jointed track and continuously welded rail to buckle due to the forces produced by the metal expanding. The threshold at which a rail may buckle is highly dependent on the condition of the track. Tracks in good condition would not be expected to buckle until 39 °C ambient air temperature. In contrast for track in bad condition, the track is at risk even at 25 °C. An example of high temperature effects could be observed in August 2003, when exceptionally hot weather in Europe caused a great deal of damage in many sectors. This extreme weather can clearly be detected in the UK network database, where 137 railway buckles were reported compared to the long-term average of 30 in the south-east region of the UK. The delays cumulated to 165,000 min, which is more than five times of those in “normal” summers.

An additional increase in delays can also be noted at lower temperatures. Cold weather poses an alternative set of problems for the rail network such as frozen points, and damaged rails due to tension cracking.

2.3 Airports, airlines and air travel

The strong and persistent winter conditions in the end of 2010 caused problems in supply with de-icing substances and the clearance of movement surfaces to reach an acceptable breaking action at major European airports. A review of winter maintenance practices at Scandinavian and Canadian airports clearly indicates that three factors are decisive for avoiding winter-related problems: an early recruiting and training of staff for winter maintenance, use of high quality equipment in sufficient quantity and the availability of sufficient runway capacity to perform maintenance. In particular, the latter point seems problematic for the major hub airports.

Convective weather poses a problem for the efficient airspace and airport operation. Thunderstorms and related phenomena can close airports, degrade airport capacities for acceptance and departure, and hinder or stop ground operations. Convective hazards en route lead to rerouting and diversions that result in excess operating costs and lost passenger time. Lightning and hail damage can remove aircraft from operations and result in both lost revenues and excess maintenance costs. With 2001/2002 data from the USA, it is estimated that the vast majority of the warm season delays are due to convective weather (DOT 2002).

A statistical analysis of flight schedule data of two US airlines (Rosen 2002) concludes that hub-and-spoke airline schedules and thus hub airports are much more affected by weather impacts than point-to-point systems or smaller airports, and that snow constitutes the major challenge for flight operations. The extra costs for detouring hurricanes have been estimated by Quan et al. (2002) for the USA ranging from US \$51,000 to US \$225,000. Weather, in particular poor visibility, low clouds and strong winds at the destination airport, is responsible for approximately 35 to 50 % of non-airline-related delays, costing approximately €900 million annually (ICAO 2009). The comparison between flight performance in the US and in Europe (EUROCONTROL, FAA 2009) reports extreme weather being responsible for 1 % of delayed flights in the USA and concludes the same order of magnitude for Europe.

Another critical issue concerns the increasing dependence of scheduled transport modes, and in particular aviation, on computerized systems. These include air navigation, instrument landing procedures, passenger process, check-in procedures and others. In particular, thunderstorms can create power failure, and many airports lack backup systems for bridging long-lasting events. A quick look in the internet reveals that power outages at airports are not a rare event and that consequences are always complex and long-lasting. With even more computerized operations, the cost of a power failure will probably decrease even more in the years to come and also make air transport much more vulnerable to interference in power and computer systems due to weather extremes. Besides aviation, power supply failures can impact train control systems, rain traction energy as well as gasoline pumps at filling stations.

2.4 Inland navigation and maritime shipping

A review of international research projects and port reports lists the extreme weather events that have the biggest impact on the inland waterway sector. Floods are causing high water levels and are possibly resulting in a lack of bridge clearance and, if critical values are exceeded, lead to the disruption of traffic. Drought periods are causing low water levels and are resulting in lower load factors, lower speeds, more fuel consumption and possibly a

disruption of traffic (in particular for bigger vessels). Finally, ice is causing severe delays or a blockade for the inland waterway vessels.

The most relevant extreme weather events for maritime transport are (1) storms and hurricanes, followed by heavy rains, high wind speeds and, sometimes, hail, causing all kinds of damage, from infrastructure destruction to the impossibility of accessing the port, as well as (2) extreme frost periods and icing, causing a temporary blockade of the port activities.

2.5 Multimodal issues

Transport networks are connected by airports, railway stations, ports and intermodal terminals, and such are considerable shares of passenger trips and freight movements. In particular in air and waterway transport, travelers have to reach ports and airports by car, train or public transport. In freight transport, trucking constitutes the most common mode for reaching transshipment terminals to load and unload cargo to and from ships or trains.

As natural disasters typically do not affect one mode only, these highly connected modes, which are dependent on feeder traffic from other modes, thus suffer twice. It is not only the main haul by air, ship or train, but also the access or the interchange or transshipment process itself, which can be delayed or blocked by severe weather conditions. To complicate the picture a bit more, it is not only passengers or shipments, i.e., the customers of the transport undertakings, but also the production process of the transport undertaking itself can be affected. This may be staff of airports, airlines, ports, ships, railway stations or train crews as well as materials such as catering or fuels.

Another important intermodal issue is the cooperation or non-cooperation of modes in the case of natural disasters. Even if all modes are hit, the level of disruption will most likely not be equal across all modes. In the positive case, passengers and goods can temporarily change mode to maintain trip and shipment chains. But in many cases, timely and reliable information is rare and the change requires a considerable organizational effort. For instance: the 2010 ash cloud over Europe has shown that the ability of railways to quickly organize transfers for stranded passengers from southern Europe to the north was lacking.

In the WEATHER project, on which we report in this paper, we took a purely uni-modal perspective. Accordingly, we cannot provide numbers of economic costs due to intermodal disruptions hereinafter. However, on a qualitative level we can say that due to disruptions in access and egress services, the vulnerability of rail, air and waterborne transport shall be well above the pure intramodal damage costs. In the second case, i.e., the replacement of main hauls, the availability of alternatives should have a damping effect on disruption costs as intermodal transfers increase the resilience of the entire system where these alternatives are available. Without detailed calculations, we cannot say which effect is stronger, but we are confident that great regional differences are related to the availability of alternatives, their capacity and the level of the provision of timely information.

3 Estimating current damage costs

This section provides an overview of the basic philosophy and the dimensions of the cost accounting framework applied by the WEATHER project for estimating today's damages imposed by extreme weather conditions on transport systems and for forecasting these to the period 2040–2050. While we can only touch the very basics of our rather complex

procedure in this article, a detailed description of methodological issues, data sources and results is provided by WEATHER Deliverable 2 (Enei et al. 2011) for current costs and by Deliverable 1 (Przyluski et al. 2011) for wider economic impacts and cost forecasts to 2050.

The WEATHER project was started in December 2009 with the aim of quantifying the entrepreneurial and social costs of weather extremes on transport for the entire European Union, all modes and a large variety of weather phenomena. To that time, only some fragmented assessments of the costs of natural hazards on transport have been available mainly from overseas (TRB (2008) for the USA, Lemmen and Warren (2004) for Canada and Gardiner et al. (2008) for New Zealand). Although these studies took the national perspective, none of the sources was able to report on the overall economic costs that climate change and extreme weather events impose on the transportation sector across the respective countries. Reliable damage cost information, however, is essential for prioritizing transport adaptation activities against other public duties, including adaptation in different sectors, as well as to balance funding between adaptation and mitigation strategies. Apart from the sister project EWENT, of which approach and results are described in Sect. 5.4, the WEATHER project thus constituted the first multilateral exercise of this type.

There are several ways of approaching the economic costs of weather extremes. First, one can analyze the incidents that happened in the past and derive statistical measures of damage probabilities. In this case, no detailed mapping of weather phenomena is required; it has just to be agreed on which types of incidents are considered and which impacts shall be accounted for. Second, one can make use of statistical relationships between weather variability and transport sector costs. The derived damage cost functions then have to be applied to current or future weather and climate patterns in order to arrive at area-wide damage cost values.

In the second case, we thus explicitly look at the triggering events and the vulnerability of the system expose to these. Triggering events or exposure denote weather extremes and the development of frequency and severity by category of extremes and European region. Looking at the vulnerability of transport systems, we need to consider the density and value of infrastructures and the level of transport activities by region, and thus by level of exposure. Further, the level of physical adaptation measures in place and—even more important—the level of preparedness of agencies and transport companies and the future development of all of these characteristics determine transport system's ability to withstand severe weather conditions. A further caveat is that the assessment of extreme weather damage costs also depends on the quality state of infrastructures. The more the infrastructure benefits of a good maintenance, the lesser the damages are likely to be. However, in the context of this project we assume that an average level of maintenance is applied, so that the impacts on costs are basically to attribute to the intensity of weather extremes.

Within the WEATHER project, the two mentioned approaches have been mixed to determine current damage costs to the transport sector. However, with regard to data situation, details of the methodology varied considerably depending on weather phenomenon, mode of transport, region and affected assets or agents. For the forecast to 2050 weather extremes, i.e., the triggering factors, and the state of the transport system, i.e., the system vulnerability have been considered by single scenarios rather than by a range of possible developments. These will be presented in the subsequent Sect. 4. In the subsequent sections, we go across the most relevant out of these dimensions, which have been considered in the WEATHER accounting framework:

3.1 Cost categories and actors affected

The nature of impacts caused by weather extremes can be described in cost categories. These might be damages of assets, the need for repair, accidents, travel time increases, etc. Accordingly, cost categories also determine the type of agent affected by the hazard. The WEATHER assessment framework structures the direct impacts of meteorological hazards and their consequences on transport into six cost categories. These are briefly described in turn.

- *Infrastructure assets*: These subsume all costs to the network operator associated with the destruction or damage of transport infrastructures, i.e., replacement in case of total loss and repair in case of partial damages. Replacement and repair costs are related to the actual age of the affected asset, i.e., we only account its time value rather than for gross renewal costs in order to reflect better the real economic burden.
- *Infrastructure operations*: These denote the costs associated with the maintenance of traffic operations and traffic safety under adverse weather conditions. These are mainly traffic police and fire brigade missions as well as winter maintenance.
- *Vehicle damage costs*: These describe destroyed and damaged rolling stock due to accidents and direct weather impacts. Here we account for the insured value as we can assume that most vehicles are insured.
- *Vehicle operations*: These describe the additional fuel consumption and wear and tear costs which motorists or fleet managers face when vehicles are caught by extreme conditions or when dangerous spots or closed infrastructures have to be detoured.
- *Time costs*: These are similar to vehicle operating costs, but describe the immaterial value of extra travel time due to weather extremes. Unit costs take into account transport sectors (passenger or freight), travel purpose (business or private) and the mode of travel.
- *Accidents*: These finally assess the immaterial costs of injuries and fatalities on top of vehicle assets. The underlying unit costs take into consideration the immaterial value of a statistical life (VSL) for different degrees of fatality as well as medical treatment, justice, insurance administration and traffic police.

Beyond accident consequences, other external costs are not subject of this study than. These occur for example in form of CO₂ emissions of additional vehicle operations, but are presumably of negligible magnitude. Details such as how these six cost categories are computed by mode and type of hazard are given in Sect. 4.

3.2 Weather phenomena and consequent events

Considered are basically all types of weather extremes ranging from heat and cold, precipitation, snow and hail, storms and storm surges to consequent events such as floods, landslides, avalanches and wild fires. In total, we have identified eleven basic types of extremes, which were then classified into four categories of typical extreme weather and climate conditions in order to reduce the degree of complexity in the assessment process. These four categories can further be classified into sudden hazards and longer periods of unfavorable conditions.

The decisive question in this context is: What is extreme? In meteorological terms, extreme denotes conditions which differ significantly from the normal seasonal and regional conditions in terms of severity and/or duration. In order to avoid complex geographically and seasonally differentiated threshold values for the various weather events, the analysis applies the impact approach. According to this, conditions are *extreme when*

impacts or costs cannot be managed by local authorities or the affected market players. An indication for this lack of coping capacity is the reporting of the incident and its consequences in supra-regional media. The four classes of extremes and their treatment in the WEATHER accounting framework are as follows:

- *Rain&Floods*: Primary weather phenomena in this category embrace persistent as well as strong convective rainfalls. However, as for most cost categories rain itself is not a problem, we concentrated on its consequent events, which are general floods, flash floods, landslides and other mass movement. These cause damages to infrastructures and vehicles and in consequence entail operational reactions, such as detouring and delays, impacting service operating and user time costs. In the WEATHER accounting framework, we considered all flood and mass movement incidents reported by transport operators and supra-regional media to be extreme. Exceptions to this approach are road accidents, for which rain intensity matters. Here we took relationships of crash and fatality rates with respect to rain intensity from literature sources.
- *Ice&Snow*: This describes winter conditions including cold spells, heavy snow fall, snow storms and avalanches. In contrast to Rain&Floods, this category of weather events and their consequences constitutes a normal seasonal phenomenon across large parts of Europe. Thus, not each breakout of winter is to be considered as extreme. What makes winter conditions unusual hard depends on regions: while Scandinavian and Alpine countries are used to long snow and frost periods, several weeks of snow cover are rare in mid Europe and virtually impossible in southern Europe. In the WEATHER accounting framework, it was decided to consider only the 10 % longest winters in a particular region as extreme. Out of these, only the numbers of ice and snow days above the 90 % winter of the respective region are accounted for in economic terms. Only for this fraction of winter days, increased winter maintenance expenses, vehicle damages, user delay and accident rates are assessed. An exception are infrastructure damages, which accumulate over longer winter periods and thus have to be considered for the entire duration of the 10 % longest winter seasons.
- *Storms*: These mainly comprise the category of extratropical cyclones, occurring in late summer and autumn. Winter storms are allocated to the category Ice&Snow in case they appear together with snowfall or very low temperatures. As Rain&Floods, all storm events reported in supra-regional media are included in the WEATHER assessment framework. Specific threshold levels of wind speeds, durations or spatial extensions are not considered.
- *Heat&Drought*: In first instance, we consider persistent periods of hot days with the lowest night time temperature exceeding 25 °C or very low amounts of rainfall. Consequences are increased car crash rates, low water for inland shipping or heat stress for infrastructures and vehicles. An important consequent event here would be wild fires, but their damage and disruption potential on transport has not been investigated systematically in the WEATHER project.

The four categories of weather extremes and their basic characteristics are presented in Table 1.

3.3 Climate zones

We have subdivided Europe in eight climate zones:

- Scandinavia (SC): Norway, Sweden, Finland, Denmark, Estonia, Latvia and Lithuania,

Table 1 Categories of weather extremes

Category of events	Events and consequences contained	Relevant regions	Relevant transport sector impacts
Ice&Snow	Frost spells Deep snow cover Avalanches	Central and northern Europe, mountain areas	Airports, roads, rail tracks, channels
Rain&Flood	Persistent rainfalls Hail Flood/flash floods Mass movements	All Europe, particularly mountain areas	Roads and rail tracks; inland navigation
Storm	Extratropical cyclones Winter/snow storms Storm surges	Western Europe, coastal areas	Rail aviation operations, sea shipping
Heat&Drought	Heat spells Droughts Wildfires	Continental eastern and particularly southern Europe	Inland navigation, rail and road infrastructure

Source: Fraunhofer ISI

- British Islands (BI): UK and Ireland,
- France (FR),
- Mid Europe (ME): Germany, Belgium, the Netherlands and Luxembourg,
- Europe East (EA): Poland, Czech and Slovak Republics, Hungary, Romania and Bulgaria,
- Alpine Arc (AL): Switzerland, Austria and Slovenia
- Iberian Peninsula (IP): Portugal and Spain, and
- Mediterranean area (MD): Italy, Greece, Cyprus and Malta

For reasons of availability of statistical and meteorological indices, we have allocated entire countries to one particular climate zone. While for most countries this approach works well, it is more difficult for others with rather heterogeneous topographical structures. This is in particular the case for Italy and France, which are partly very mountainous. We finally allocated Italy to the Mediterranean countries as this is the climate zone for the major part of the country; for France, an extra climate zone was defined. In contrast, the EWENT project subdivided countries like Italy and assigned them to different zones. A mapping of the eight climate zones is given by Figs. 1 and 2 further down in this paper.

3.4 Modes of transport

Considered were all modes of transport, namely road, rail, aviation, inland navigation and maritime shipping. Generally it was not distinguished between passenger and freight transport as most impacts of extreme weather affect the infrastructure. A special case, however, was combined road–rail freight transport, which was considered a separate mode. The application of the weather cost assessment methodology varied considerably between modes as follows:

- *Road*: As described above, here a mix out of the assessment of media and infrastructure operator reports (incident database, IDB) and damage functions from literature together with regional weather data (elasticity of extremes model, EEM) was applied. The IDB analysis was undertaken for six European countries, namely Germany, the UK, the Alpine countries and the Czech Republic.

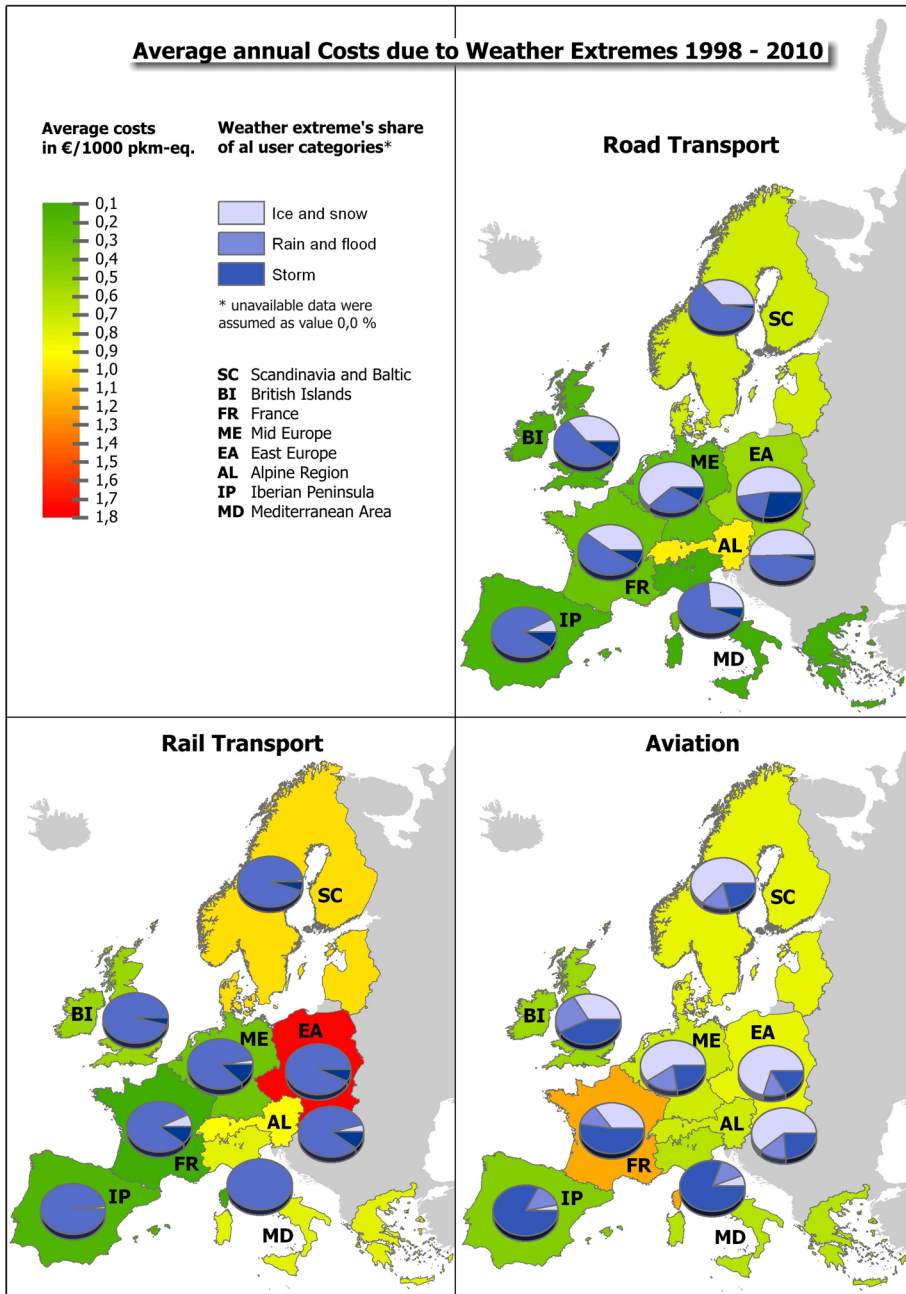


Fig. 1 Average damage cost estimates 1998–2010 by mode and climate zone. *Source Fraunhofer ISI*

- *Rail*: For the rail sector, only the incident database (IDB) approach was applied. Through operator data for specific incidents in Austria, Switzerland, the Czech Republic and Germany, average costs and cost deviations per type of event for the most critical weather phenomena could be derived.

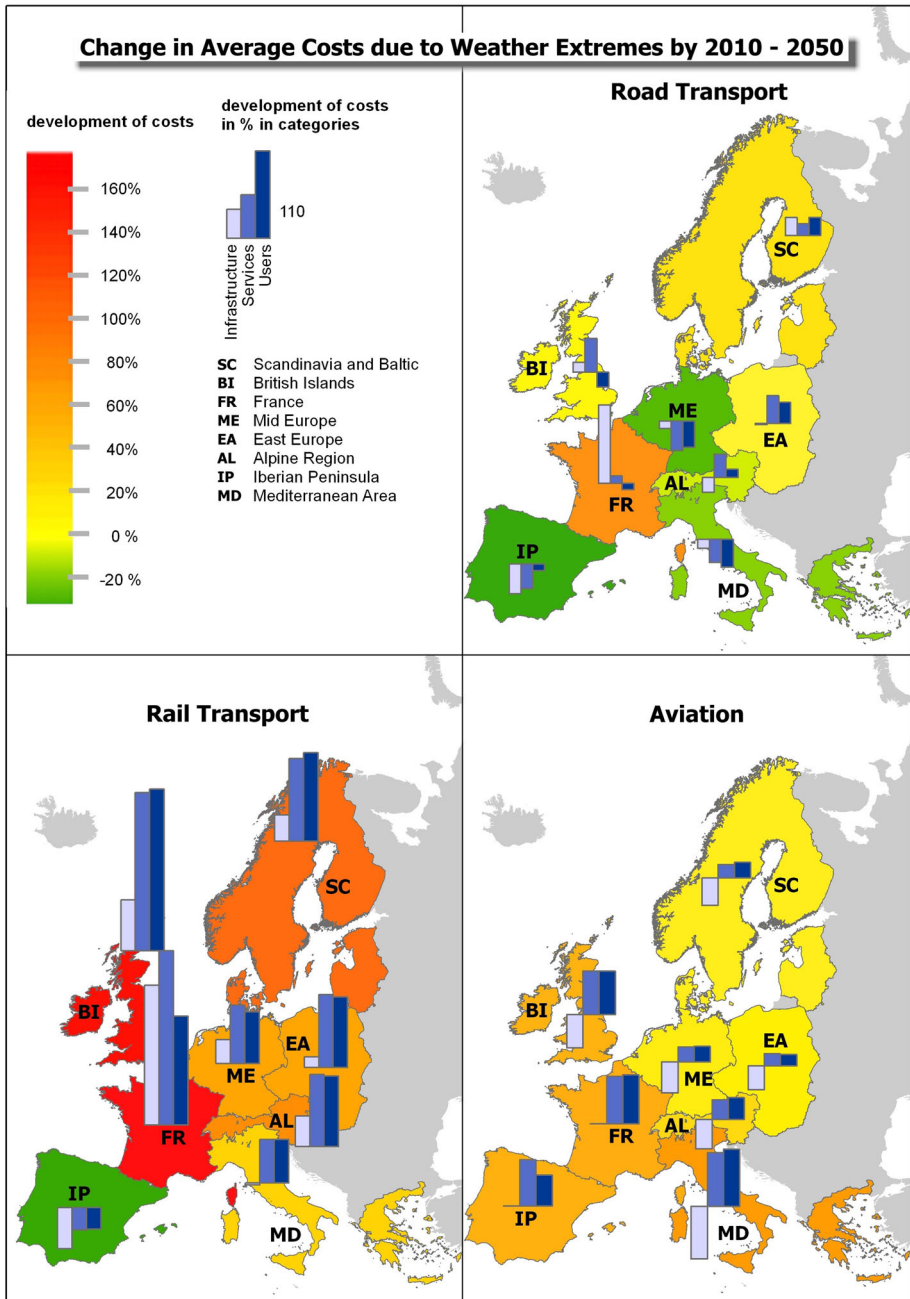


Fig. 2 Average damage cost forecasts 2040–2050 by mode and climate zone. Source Fraunhofer ISI

- **Aviation:** We have considered airport and flight operations. Airport winter management was assessed by valuating snow and ice days above the 90 % winter with average unit costs per flight from Scandinavia. Delay costs to airlines and passengers were estimated

using EUROCONTROL delay statistics and the estimated impact of extremes from EUROCONTROL/FAA (2009). Safety costs were based on EASA reports on incidents by cause and purchase values of aircrafts. The majority of safety costs are caused by general aviation.

- *Shipping*: The waterborne modes include inland navigation on rivers and channels, as well as coastal/short sea and maritime shipping. Although in some parts of Europe passenger ferry services play a significant role, the analyses in the WEATHER project have concentrated on freight transport in inland navigation.

4 Data, cost estimation and generalization

As the major lines of our accounting system had been introduced above, the present Sect. 4 turns to the more critical question of data availability and concrete calculation mechanisms. Both are not independent of each other: extreme weather is not at all a clear cut category in which public asset or transport statistics are reported. Thus, we need to work with indications, hints and rough approximations of damage costs, which can be attributed to weather extremes. This holds for the estimation of current damage costs in a defined region as well as for their transfer to other spatial—and partly climate—contexts and for their prediction over time.

First, we delve into the question of estimating current road transport-related damages in mid Europe as roads constitute by far the largest cost block. Then we turn to rail, aviation and waterborne traffic before describing the procedures and results for cost generalization across Europe and for forecasting them from now to the period 2040–2050.

4.1 Physical impacts 1998–2010

The recording of the physical impacts of weather extremes, comprising damages to assets, additional operations, safety and delays, strongly differs by mode. For road transport, a hybrid approach combining the impact elasticity values with respect to weather parameters found in literature (extremes elasticity model EEM) with a media and transport operator database on actual events (IDB) was applied. From information in the literature on the propagation of accidents and delays during heavy precipitation, crash rates with heat days and infrastructure costs under winter conditions could be derived. These were then applied to average annual ice, snow, heat and heavy precipitation days provided by the ECA&D database (ECA&D 2011).

The incident database is again composed of two elements: a media review containing around 950 entries for six countries from 2000 to 2010 and recorded damage data provided by network operators in Austria (ASFINAG) and the Czech Republic. The countries covered by the IDB are Germany, Switzerland, Austria, the UK, the Czech Republic and Italy. Evaluated were supra-regional media from 2000 to 2010. As older reports are likely to be taken out of archives and the online presence of newspapers in the early 2000s was not as high as today, data contain some bias toward more recent events. The resulting roughly 1,000 datasets were transformed into standard events, which may be related to only one specific or to several out of the six cost categories. Examples of simple standard events are reports on delays or fatalities. Complex events are, for instance, the destruction of a road, entailing capital costs for repair and rehabilitation, police and traffic management and vehicle operation due to detouring during repair. For each standard event, default parameters for duration, extension and costs of

Table 2 Data availability for cost generalization

Overview of the availability of cost estimates in road transport EEM: Extremes elasticity model IDG: Incident database	Rainfalls	floods	Mass-movements	clones	Storm surges	storms	Frost periods	Snow	Winter storms	Heat periods	Droughts	Wild fires
Infrastructure assets	⊗						▨	▨		⊗	⊗	⊗
Infrastructure operations							▨	▨		⊗	⊗	⊗
Vehicle assets	⊗									⊗	⊗	⊗
Transport service operations										⊗	⊗	⊗
Safety issues	■						▨	▨		■	⊗	⊗
Congestion and delays	■	▨	▨	▨			▨	▨		■	⊗	⊗
Data sources:	■ EEM	▨ IDB	▨ Both				No data		⊗ Irrelevant			

Source: Enei et al. (2011)

the six basic cost categories have been predefined, but the database allows these to be modified by event-specific adjustment parameters. Table 2 gives an overview of the two approaches contributing to the overall estimate of specific annual costs to road transport by actor and type of extreme. The overview reveals that still some considerable gaps remain, in particular concerning storms, storm surges and wild fires.

4.1.1 Rail

In the case of rail transport, media and transport operator data have been compiled for selected extreme events. Considered are heavy and permanent rainfall with ensuing floods and mass land movements, thunderstorms, winter storms and avalanches. Although there is detailed information on heat impacts on delays and train operating costs from the FUTURE-NET project (Dobney et al. 2009), these are considered specific to UK networks and thus are not taken into account in the WEATHER project.

Distinguished are capital, operating and user costs, which are expressed as minimum, maximum, average and median values. Moreover, the replacement or repair of tracks, increased service operation due to detours, replacing bus services or revenue losses due to canceled trips, cleaning and reopening of tracks and user time losses are considered. Safety impacts are omitted as there is a strong tendency in Europe to put safety in first place and thus to accept operation costs and delays rather than to increase accident risks.

With some extrapolation, annual total costs of €305 million are derived for Europe. Additionally, with the hypothesis of +10 to +20 increases in operating costs due to rain, floods, storms and snow, additional annual costs of €6.8 million are derived, which leads to total costs of extreme weather events of €312 million.

4.1.2 Air

The assessment of air transport is again based on combining average risk factors, mainly from US sources, with assessments of European air transport databases and literature reviews. Datasets used are the Eurocontrol customer database (EUROCONTROL 2011b) and accident data provided by the European Air Safety Agency. Though a large number of cost categories could be filled by this approach, problems remain in transferring US results

to European conditions and concerning the identification of delays and accidents due to extremes. The €360 million overall annual costs, which extreme weather conditions are found to cost to airports, airlines, passengers and air cargo forwarders, are considerable.

4.1.3 Shipping

With water level data of the river Rhine in Germany and a literature review on associated economic costs, the impacts of droughts and persistent rainfalls with floods could be estimated. The Rhine is by far the most important shipping route in Europe, which makes the results sufficiently representative for Europe. A comparable analysis for coastal and maritime shipping has not been carried out.

4.2 Monetary valuation

To derive the total economic losses by cost category or actor, the physical impacts were assessed using the following evaluation principles (compare Enei et al. 2011 for more details):

- *Infrastructure assets*: These were assessed by current replacement costs, multiplied by the age structure of the assets. Using German data, these are €8.7 million per kilometer for completely destroyed motorways and €2.55 million per km for railway lines. Depending on the intensity of the extreme and the type of damage, a deduction of this value was applied.
- *Infrastructure operations*: These were estimated at €1,000/h for police and traffic control on motorways, €5,000/h for fire brigade missions and €43,600 for operation and revenues losses per railway section.
- *Vehicle damage costs*: These are derived from insurance statistics for roads, and aircraft industry reports for aviation, also considering the age structure of the vehicles involved.
- *Vehicle operations and time delays*: These were assessed by average detour lengths derived from network models and by applying values of travel time delays of around €13/h and passenger taken from van Essen et al. (2011).
- *Accidents*: Assessed are the immaterial costs of injuries and fatalities by the value of a statistical life (VSL) of €1.6 million per death casualty and 15 % of that for severe injuries. On top of these, medical treatment, production losses and administrative costs are calculated according to van Essen et al. (2011).

The resulting total annual costs then were deflated to 2010 values using annual national inflation rates from EUROSTAT statistics. Dividing these total economic costs finally by the 12 years of the period 1998–2010 finally resulted in average annual losses for the countries covered by each modal analysis.

4.3 Value transfer and forecast methodology

A simple value transfer model consisting of key meteorological indicators of extremes from ECA&D (2011), plus transport network lengths, passenger and ton kilometers for each of the eight climate zones was applied, in order to obtain an idea of cost levels across Europe. To remain with the logic of triggering factors and transport system vulnerability, the relative level of indices of extremes by category denotes the difference in triggers—or exposure—in the target regions relative to the countries where the original damage data has been generated. The structural indicators of the transport networks, i.e., length, passenger-

and ton kilometers per km², then denote the relative system vulnerability. Other important factors, such as the level of adaptation and preparedness or the maintenance status of national infrastructures, have been neglected.

The meteorological indices were derived from a selected number of weather stations in each of the 29 European countries. Here we selected the stations near the biggest cities as the weather activities there affected most people. For each of the four weather categories, the following weather indices for the period 1998–2010 were extracted from the ECA&D database:

- *Rain&Flood* = number of events with 5 or more consecutive days with rain >20 mm,
- *Ice&Snow* = number of days with T_{max} ≤ 0 °C OR snow depth >1 cm above the 90 % winter length
- *Heat&Drought* = Number of days with T_{min} ≥ 25 °C above the 90 % summer length.

As the ECA&D dataset does only hold temperature and precipitation data, indices for storms by country were taken from the ESPON project (Schmidt-Thomé 2006).

For generalization, we selected the set of countries per mode and weather categories with the most reliable datasets. For these, we computed average costs per network kilometer (infrastructure assets and operations) or weighted passenger and ton kilometers (all other cost categories). Total costs for all other countries were then computed simply by multiplying these unit costs by the country's number of extreme days and the network length or transport demand.

4.4 Forecast to 2040–2050

Forecasts of vulnerability measures are generated using EWENT Project forecasts of extremes (Leviäkangas et al. 2010) in conjunction with transport sector projections from the GHG-TransPoRD study (Fiorello et al. 2012). These indicators are provided by mode and region and are linked by assumptions on average cost elasticities with respect to the frequency of extremes and the density of transport demand. As for the generalization of damage costs across Europe, we can translate these elements into the terminology introduced above. The forecast of frequencies of extremes represents the development of triggers for damages. Here we receive a mixed scenario of positive and negative developments: Vulnerability is then described by the two factors of transport infrastructure and system development and by the relative impact of changes in the trigger, i.e., the cost elasticities. Due to different population development lines also here we receive a mixed scenario of increasing and decreasing vulnerability.

Again, we assume that besides the density of infrastructures and transport activity, the vulnerability of each system element in 2050 is the same as in today. This might not be the case as many countries initiate adaptation programs. However, in the WEATHER project we were keen on getting a first idea of the order of magnitude of the consequences of weather extremes. The exploration of details, including sensitivity analyses, was devoted to later research.

The main findings of the forecast are as follows:

- Warmer wetter winters. This phenomenon is persistent across Europe reducing frost and snow days. Throughout the year flood risks will increase.
- dryer hotter summers with particular problems to southern Europe. While average summer temperatures increase, heat spells are expected to increase in frequency and in maximum temperatures.

- More storms will hit the continent with most impacts at the Atlantic coast, where already now the highest storm activity is present.

For projecting the intensity of weather extremes in the coming four decades, results derived from six RCM models, run by the ENSEMBLES project and described by the EWENT project, are applied. The values provided by the upper half of Table 3 denote the number of days increasing or decreasing from 2000–2010 to 2040–2050 per type and intensity of extreme. These values have been related to the current intensity and frequency of weather extremes derived from the ECA&D Database (ECA&D 2011) to arrive at relative changes of frequencies of weather extremes.

In a second step, the exposure of the European transport systems in 2050 relative to 2010 is estimated. System conditions in this context include infrastructure assets and their age as well as transport activities in terms of vehicle kilometers, passenger trips and goods movements. We express transport activity by passenger kilometer (pkm) equivalents (pkm-eq). The equivalent per ton expresses the use of infrastructure capacity and the transport costs of one ton of goods relative to a passenger. For road and rail, we use an equivalency factor of 0.3, while for aviation we use a factor of 10. The forecasts of demand and infrastructure supply presented in the lower half of Table 3 were generated by the European System Dynamics Transport and Economy model ASTRA.

With some intuitive cost elasticity values, we have tried to catch the main specificities of the categories of extremes and their impact on transport networks and services. By expert judgment, these were set as follows:

- Winter impacts prove to cause massive costs only at their onset. This implies that a simple prolongation of winter periods will cause under-proportional economic costs as people and transport professionals get used to the conditions. Thus, we use an elasticity of 0.5.
- Rain, flood and storm events are, in particular floods and storms, commonly singular events for particular regions. An increase of rain and wind days thus may in many cases imply to spread the occurrence of floods and storms across the country. Accommodation effects are thus less likely. We thus use an elasticity of 0.8.
- The cost relevance of heat periods is contrary to winter impacts. In particular, long heat periods start causing costs to operators and users. Thus, we here use an elasticity of 1.5.

5 Results

5.1 Total and average costs 1998–2010

The analysis across all modes, weather categories and European regions as described in the previous section leads to overall annual costs of €2.5 billion. Considering that this value constitutes an annual average, including mild years with only few extreme weather situations, this number is significant. When interpreting it, we should recall that these costs do not express the full costs of all winter or heat periods, but of their extension beyond the 90 % snow and ice or heat period. Moreover, we must accept a certain level of underreporting, as our analyses are incomplete, not encompassing all modes and weather categories.

Not surprisingly, the vast majority of costs are calculated for road transport. But rail, including intermodal transport (13 %), and aviation (19 %) also account for a considerable share in total costs related to weather extremes with respect to the past decade (Fig. 1). No

Table 3 Forecast indicators for extreme days and transport sector performance

Category	AL	BI	EA	FR	IP	MD	ME	SC	EUR29
<i>Absolute changes in frequencies 2000–2010 to 2040–2050</i>									
Ice&Snow, Tmax <0 °C	-10	-5.5	-8	-5	-1	-3	-8	-12	
Rain&Flood, rain >150 mm/d	0.1	0.1	0	0.1	0.1	0.1	0.1	0.1	
Storm, wind speed >35 m/s	0.1	0	0	0	0	0	0	0.1	
Heat&Drought, Tmin >25 °C	5	1	10	8	15	15	5	0.3	
<i>Relative changes in Frequencies 2000–2010 to 2040–2050</i>									
Ice&Snow	-12 %	-20 %	-4 %	-20 %	-50 %	-50 %	-12 %	-5 %	
Rain&Floods	44 %	45 %	8 %	194 %	-48 %	0 %	39 %	33 %	
Storms	5 %	7 %	-2 %	0 %	13 %	20 %	3 %	2 %	
Heat&Drought	72 %	100 %	104 %	400 %	39 %	15 %	167 %	30 %	
<i>Assumed changes in transport infrastructure assets 2010–2050</i>									
Road	14 %	18 %	52 %	17 %	44 %	19 %	7 %	39 %	27 %
Rail	19 %	40 %	30 %	15 %	20 %	23 %	16 %	24 %	23 %
Air	46 %	48 %	47 %	42 %	44 %	43 %	40 %	40 %	43 %
<i>Assumed changes in transport demand (pkm-eq) 2010–2050</i>									
Road	28 %	36 %	103 %	34 %	88 %	38 %	15 %	78 %	47 %
Rail	75 %	159 %	122 %	61 %	80 %	92 %	64 %	97 %	87 %
Air	91 %	95 %	95 %	84 %	87 %	87 %	80 %	80 %	87 %

Source: ARPA-ER and Fraunhofer-ISI based on EWENT results

generalization of the Rhine-based results for the inland navigation sector has been carried out for Europe so far. But we can also expect considerable costs here.

When comparing the modal situation in a more qualitative way, the analyses indicate that much of the infrastructure-related damage is subject to proper maintenance. Thus, there is a trade-off between damage costs and increased network servicing activities. In the case of network and fleet operations and consequent impacts on user delays and safety, damage costs in many cases are driven by the preparedness of the transport sector. This is particularly evident in the case of winter impacts in western and central Europe. In comparison with the winter-proof Scandinavian countries, the UK, France, the Benelux countries and Germany were hit extremely hard by the conditions of the past winter seasons, which occurred after some decades of rather mild winters.

The picture across weather categories and climate zones is presented by the modal maps in Fig. 1. The screening of average costs by passenger kilometer reveals that the rail sector is rather vulnerable with hot spots in Eastern Europe, the alpine region and Scandinavia. But in general, aviation with special reference to France shows highest average costs figures, while road transport, due to its high market share, in average is least affected.

The economic costs computed by the methodology laid out above represent the direct damages imposed on the transport sector based on the experiences of the past decade. The underlying assumption that we focus on the very extreme events is of course debatable. Figures of the parallel project EWENT reveal that one might arrive at damage figure 10 times above our results when all adverse weather conditions enter the equation.

Another issue that is left unconsidered by the above damage values is the indirect costs which failures in the transport system impose on the rest of the economy. Przulski et al. (2011) estimate these costs amounting to roughly 20 % of direct damage costs, i.e., around 5 million euros annually for the European economy. These indirect costs include production losses due to delayed or canceled deliveries or business trips or damages of cargo. Some double counting might be the case as the figure also considers the wider impacts of infrastructure damages and the accident consequences for undertakings and the public health sector.

5.2 Case study: intermodal freight transport

The mode-specific analysis of vulnerabilities gets problematic when transport chains involve several means of transport. This is the case for combined freight shipment as well as for intermodal passenger trips. It can be suspected that the interchange between modes creates an additional risk element making intermodal chains more vulnerable to external disruptions than uni-modal shipments or trips. Here, we look at the problem with the example of combined freight transport.

As for the special case of intermodal freight transport, the following application example describes its specific impacts:

Generally, the vulnerability to some extreme weather events, e.g., heavy storms, rain and ice, is lower than in other transport means, e.g., trucks in pure road transport, due to the heaviness of the intermodal transport infrastructure (track keeping in line vehicles, gantry cranes, intermodal wagons, loading units, terminals, etc.). On the other hand, the intermodal freight transport network is less flexible due to the limited number of lines in the railway network that are able to meet the technical requirements allowing combined transport (e.g., Seidelman 2010). Therefore, once an interruption, for example by avalanches, happened, it does have a major impact.

Table 4 Potential impacts of climate change on intermodal freight transport

Potential climate change extreme weather events	Impacts on Intermodal land transportation	
	Operation	Infrastructure
Temperatures increases in very hot days and heat waves	Mild: vehicle overheating and tire deterioration	Mild: rail track deformity
Change in seasonal precipitation and flooding patterns	High: frequent interruptions, increases in weather-related delays	High: flooding of road/rail lines, tunnels, landslides, damages to road and tracks
Increase in drought conditions	Medium: wildfires reducing transport activities	Medium: wildfires threatening intermodal infrastructure
Increased intensity in storms, winds and waves	High: debris on road and rail lines, interruptions	High: increase probability for infrastructure damages, supports, lighting fixtures, etc.

Source: Adapted from Committee on Climate Change and US Transportation, National Research Council (TRB 2008)

The following table provides a qualitative evaluation of the climate change weather-related events and their likely impacts on intermodal transport (operation and infrastructure) (Table 4).

The table shows that the extreme weather events potentially affecting intermodal transport are mainly flooding, landslides and avalanches, to the extent that they are causing delays in operations or interruptions in transport services. Damages from extreme temperatures, winds and intense precipitations can be considered of minor importance, due to the heaviness of intermodal infrastructures. However, it should be considered that heavy rain and winds can hamper terminal operations with swinging loads, ultimately reducing productivity and causing delays.

More specifically, the list of the components of the intermodal transport system most likely to be affected by climate change is the following:

5.2.1 Infrastructure

- *Road and rail infrastructures design:* The impacts are manifold, e.g., from the development of new, temperature-resistant paving materials for road and rail lines, to the use of insulation material for extreme low temperatures. In case of high risks of flooding and landslides, even the relocation of road and rail sections to more secure locations may be incurred to infrastructure planners and managers. Increases in drainage capacity for new transportation infrastructure. Will be necessary all over Europe, but should be possible at low costs during standard maintenance cycles.
- *Maritime and airport infrastructures design:* Increase the robustness of port infrastructure from waves and storm surges. Check and improve the protection of terminal, cranes and other dock facilities and warehouses. Development of new temperature-resistant runway paving materials should reduce airport maintenance costs in heat prone zones.
- *Rolling stock design and construction:* In rail intermodal transport, technical standards for wagon construction (combined transport) take account of devices for contrasting the effects of side winds.
- *Infrastructure maintenance:* Additional maintenance costs may be incurred to infrastructure managers due to drainage canals near coastal roads and rail infrastructure sections, cutting trees along the road and rail infrastructures.

Facing the climate change impacts, it can be said that the most likely vulnerable elements are infrastructure maintenance and technical design.

The vulnerable elements of combined transport *operations* are twofold: Firstly, the time costs for delays in good distribution, secondly the complete interruption of service, e.g., by the closure of lines.

Cost estimation has been carried out on the basis of several sources:

- Infrastructure damages: estimates from recent damages due to extreme weather events, e.g., the interruption of the lines in Chiasso and Luino in 2002 due to landslides
- Infrastructure operating costs (maintenance and repair) and additional costs on the service provision (operators), from the European research project on intermodal costs RECORDIT (2003), collecting operating costs along three pan-European intermodal corridors
- Social costs, i.e., accident costs, from EUROSTAT statistic and literature review concerning the impacts of extreme weather events.

Lack of data and little observations do not allow ascertaining the delays attributable to the freight transport network failures due to extreme weather events. The generalization at EU level has been carried out through the overall volume of ton kilometer of annual railway transport of goods in intermodal transport units (EUROSTAT).

The results are shown in the following table.

The assessment of intermodal transport vulnerability to climate change extreme weather events leads to €6.8 million of annual costs, borne by infrastructure managers (57.0 %) and social actors (43.0 %), i.e., the overall cost for the society due to additional accidents costs.

The allocation of costs by type of event, due to the lack of quantitative evidences through significant case studies, has been conducted through qualitative insights from the literature review. Storms, winds and strong waves, accounting by 50 % of total costs, are considered to exert a relevant influence of operational activities (use of infrastructure, loading and unloading, origin/destination trips, etc.). The same can be said for floods and avalanches, accounting for 35 % of total costs, to the extent that their impact is particularly relevant in interrupting services, and extreme temperatures (16 % of total costs), causing accidents and higher maintenance costs.

5.3 Forecasts to 2040–2050

The results provide a rough estimate of what the cost development might look like in case no specific adaptation measures are taken to make the transport sectors in the affected regions more resilient to changing conditions. Across all weather categories, we find that total costs in the road sector will increase by 7 % between the periods 1998–2010 to 2040–2050. This is not much given the strong increase of transport demand and in infrastructure assets presented in Table 5. The results here thus reflect the partly strong decline in extreme days across Europe. The developments in total costs are, however, much more expressed in other modes: +72 % in rail and +38 % in aviation. Here, the more dynamic demand development together with the anyway higher sensitivity in scheduled modes of transport offsets the reduction in extremes.

The result provide a rough estimate of what the cost development might look like in case no specific adaptation measures are taken to make the transport sectors in the affected regions more resilient to changing conditions. We are talking not only about a higher frequency, amplitude and duration of extremes, but also about a higher variability of climate events and increasing exposure levels through growing transport demand and

Table 5 Cost estimates for intermodal freight transport

Type of event	Annual costs (mil. €) by affected actor groups*		
	Infrastructure managers	Social costs (accidents)	Total
Floods, avalanches	2.1	0.3	2.4
Storms, winds, waves	1.3	2.0	3.3
Extreme temperatures	0.5	0.6	1.1
Total	3.9	2.9	6.8

Source: Enei et al. (2011)

infrastructure networks. These issues are challenges adaptation and preparedness programs.

Turning the attention from total to average costs, we eliminate the demand effect to some degree by moving the cost development figures more toward the development of weather hazards. The respective output indicators are mapped by mode climate region and distribution of weather phenomena in Fig. 2. They show the highest changes for rail transport with focus on France, the British Islands, mid Europe, Scandinavia and the Alpine Arc. In other words: railways are the losers of climate change thanks to their expensive—and therefore vulnerable—infrastructure and their complex vehicle routing system and high safety standards. The mentioned countries are those which already show the highest variability in weather conditions. With respect to changes in temperature patterns, these countries, alike the rest of Europe, need to cope with higher summer heat as well as with, although less frequent, current maximum lowest winter temperatures.

5.4 Comparing WEATHER and EWENT cost estimates

As indicated earlier in this publication, the sister project WEATHER and EWENT arrived rather different levels of damage costs for the current period. To a large extent, this is based on the accounting philosophy followed by the two projects and on entailed methodological decisions. To a smaller extent, the deviations may be explained by the coverage of cost categories, modes and countries, and by the availability and interpretation of data. The main issues can be formulated as follows:

- **Definition of extremes:** this probably constitutes the major deviation of the results. While the WEATHER project was extremely cautious in taking account of adverse weather conditions, the EWENT philosophy was to include everything that impacts the transport sector and that could be subject to change in the future. The two outputs lead to different interpretations. While EWENT seeks for the vulnerability of transport to weather variations in general, we have tried to catch the big low probability, but high impact events.
- **Basic approaches:** The EWENT methodology strictly went along established risk assessment frameworks, defining the vulnerability of systems by critical threshold values. This makes the EWENT approach from a theoretical point superior to the rather intuitive impact approach followed by the WEATHER methodology. However, in the end the practicability of one method or another raises and falls with data availability. At this point, the WEATHER approach might be somewhat more robust as it relies on a hybrid approach combining various knowledge sources. Finally, we cannot constitute that one approach systematically creates higher values than the other.

Table 6 Comparison of WEATHER and EWENT results for current total costs

Costs by 2010 Billion €2010	Road		Rail		Aviation	
	WEATHER	EWENT	WEATHER	EWENT	WEATHER	EWENT
Infrastructure assets	0.95	1.00	0.10	0.10	0.00	
Infrastructure operations	0.17	0.20	0.00		0.01	
Operations and logistics	0.11	3.50	0.13	0.02	0.12	0.00
Time delays	0.28	0.75	0.08	0.01	0.13	0.70
Accidents	0.23	10.00	0.00	0.10	0.10	
TOTAL	1.75	15.45	0.31	0.23	0.36	0.70

Source: Fraunhofer ISI based on Enei et al. (2011) and Nokkala et al. (2012)

- **Cost assessment:** The WEATHER assessment strategy to a large extent relies on synthetic standard cost values. These describe economic losses in standardized situations and are adapted to the real damage cases by scaling factors. This method is not very precise, but allows the processing of rather fragmented and qualitative input data. In contrast, EWENT was more delving into operator data. Both approaches could be combined, i.e., the WEATHER standard cost values could be improved and, where needed, diversified by better transport sector data. A particular bias of one method toward higher or lower results compared to the other, again, cannot be diagnosed.
- **Completeness of hazard considered:** The WEATHER project has considered storm, heat, drought and wind fire events only partially. Here, the event project appeared to be more complete across all weather phenomena, which partly explains the higher values there.
- **Treatment of accident costs:** in the WEATHER project we followed again a cautious approach by acknowledging that under some weather conditions accident numbers and/or severities in road transport decline as people drive more slowly or suspend trips. In contrast, EWENT has considered a fixed share of total road fatalities and injuries being caused by adverse weather conditions. The significance of this impact category for the deviation of results is visible in Table 6: accidents constitute by far the biggest cost block in EWENT, while they are only of minor relevance in the WEATHER results.

The approaches for assessing infrastructure damages and the economic unit values for attaching money values to transport accidents and fatalities (value of statistical life) and to time delays (value of travel time savings) are comparable between the studies. Thus, we can identify the different philosophy in the definition of “extremes” and the treatment of accident costs the major reasons for the huge difference in WEATHER and EWENT results. It is most probably more easy to find a consensus on the accident question than on the more fundamental question of defining extremes. But in the latter case, we could argue that one keeps two different approaches for varying rationales behind accounting for the costs of weather hazards (Table 6).

6 Conclusions

In conclusion, the WEATHER accounting model shows that extreme weather has a significant impact on transport systems. The most affected transport mode in Europe is road

transport, which bears ca. 80 % of total costs, followed by air (16 %) and rail transport (3 %). Infrastructure assets and operations account for the highest losses: 51 % of total costs (43 % asset and 8 % operations) followed by users' costs (delays and accidents). Severe winters and floods have the largest impact on the transport system, with winters accounting for 43 % of the costs and floods 39 %. The total annual costs of €2.4 billion emphasize that the problem of extreme weather events should be taken seriously and suggest that a strategy to identify, predict and mitigate the likely disruptions should be devised. It is especially critical for companies to undertake risk assessment.

Related to passenger kilometer equivalents rail (0.57 €/1,000 pkm-eq) and air (0.66 €/1,000 pkm-eq) are roughly twice as vulnerable as road travel (0.29 €/1,000 pkm-eq). This is partly due to the expensive infrastructure in rail transport. However, a high degree of vulnerability against external shocks is most likely immanent to scheduled modes of transport as here disruptions of services leads to knock-on effects spreading out to other network parts and over time. The same effect might even happen in highly interconnected just-in-time or just-in-sequence production systems in road haulage.

Looking some decades ahead, we found that climate change will create winners as well as losers with respect to the vulnerability to weather extremes. While winters will get milder but wetter, summers will get hotter and dryer and storm activity will most likely increase. In total, we found that the costs due to weather hazards will increase, but with very different rates across the modes of transport. The most sharp raise with +72 % in average costs is found for rail travel, which is thus hit most by changing weather patterns. On the other side of the scale, road transport costs will only raise by 7 %, i.e., a fraction of the cost increase in rail. Looking at these figures, we can thus argue that rail travel contributes least to global warming, but suffers most of its impacts.

Sound cost estimates of climate change and weather extremes are needed to justify appropriate mitigation and adaptation strategies. However, as the comparison of the WEATHER and the EWENT cost estimates revealed, there is still a high degree of uncertainty on the true financial burden of European transport systems. To accelerate the discussion on climate adaptation, which is partly denied in some transportation businesses, the establishment of a transparent and applicable cost estimation scheme is thus recommended. However, the numbers we have on the table right now are good enough to start adaptation planning.

At a company level, one major action is to develop a business continuity plan or contingency plan to mitigate the supply chain risks. Governments should consider appropriate measures for crisis management and disaster recovery to reduce the impacts from extreme weather. Suitable strategies often are available at low costs by raising awareness, staff education, customer information, as well as by establishing or intensifying vertical and horizontal cooperation networks. Successful adaptation mechanisms in the transport sector are elaborated elsewhere in this issue.

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