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ORIGINAL PAPER

Adapting rail and road networks to weather extremes: case studies for southern Germany and Austria

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Abstract The assessment of the current impacts of extreme weather conditions on transport systems reveals high costs in specific locations. Prominent examples for Europe are the economic consequences of the harsh winter periods 2009/2010 and 2010/2011 and the floods in Austria, Eastern Europe, Germany and the United Kingdom in 2005 and 2007. Departing from the EC-funded project WEATHER, this paper delves into the subject of adaptation strategies by revisiting the project's general findings on adaptation strategies and by adding two specific cases: (1) advanced winter maintenance on roads in southwest Germany and (2) technical and organizational measures in Alpine rail transport. For these two cases, feasible adaptation strategies are elaborated and their potential is discussed in light of damage cost forecasts up to 2050. For the road sector, we find a high potential to mitigate weather-related costs, although damages here are expected to decline. In contrast, rail systems face strongly increasing damages and the mitigation options offered by improved information and communication systems seem to be largely exploited. Consequently, it is easier to justify expensive adaptation measures for high-cost rail infrastructures than for road transport. A generic analysis of 14 damage cases worldwide, however,

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revealed that generally awareness raising, cooperation and communication strategies are sufficient to mitigate the most severe damages by natural disasters.

Keywords Road networks · Railway operations · Extreme weather events · Climate change · Adaptation · Weather information systems · Investments · Forecasts

1 Introduction

1.1 Background

The Stern Review (Stern 2006) estimates that the global economic losses due to the consequences of climate change could range between 5 and 20 % of world gross domestic product (GDP), depending on the extent of the impacts taken into consideration. The report emphasizes that, if no action is taken, by 2035, we will have doubled the CO_2 concentration in the atmosphere compared to pre-industrial levels. Irrespective of the share contributed by anthropogenic activities to rising temperatures, the global temperature will probably climb to more than 2 °C above pre-industrial levels. Even if large-scale greenhouse gas emission mitigation activities were implemented now, this cannot be avoided (IPCC 2007). Even worse, the slow progress in combating global THG emissions rather points to an unavoidable warming of 4 °C. Besides the increase in mean temperatures, consequences will include the thawing of permafrost soil and Arctic ice, a rise in sea levels, more frequent droughts and wild fires, changing weather patterns with more intense and frequent storms and rainfall and an increase in the number and extent of floods and landslides. While the measurable changes will most likely remain moderate in the next three to four decades, major changes will be visible by the end of the twenty-first century. The costs resulting from extreme weather events are already rising. With economic losses amounting to some 380 billion US dollars, 2011 was the most expensive natural disaster year to date (Munich 2011). Although every country will be affected, the poorest countries will suffer the earliest and the most (Stern 2006). Thus, the vulnerability of the population in developing countries may constitute one of the major threats of climate change. Toward the end of the century, major impacts will be experienced in the health, agriculture and water supply sectors.

Given the long life span of many infrastructures, it is self-evident that a certain level of adaptation will be required, regardless of our success in curbing greenhouse gas emissions. Generally, we can state that the costs of inaction are much higher than a sensible mix of mitigation and adaptation activities (Stern 2006; IPCC 2007; EC 2007). Therefore, the European Union has introduced the European Emissions Trading System (ETS), and many countries inside and outside Europe have drawn up or at least initiated climate adaptation plans (EC 2007). However, Patt et al. (2010) stress that the relationship between adaptation and mitigation is complex, and indeed, it cannot be determined to what extent the optimum level of one depends on the other.

It is commonly assumed that transport is not the sector affected most by climate change. Agriculture or urban developments near coastlines and rivers are expected to face higher costs as temperatures and sea levels rise. Moreover, in a global context, Europe is rather privileged in terms of climate fluctuations and weather extremes. To this extent, climate change impacts may seem to be a relatively minor problem for the European transport sector in general. But even if these assumptions hold true, the past decades have shown that there are certainly vulnerable elements within the European transport sector, which entail risks to the economy and social life, and which are worth looking at in more detail.

According to a literature review by Osberghaus and Reif (2010), transport, together with the health sector, is characterized by large uncertainties in conjunction with potentially high adaptation costs in the future. Rough estimates suggest 4 billion Euros annually in the 2060s and 5.7 billion Euros in 2050 for Europe, mainly for coastal flood protection and public transport. However, a later publication by Altvater et al. (2012) states that the data about the costs and benefits of adaptation measures in transport are extremely poor, and there is a lack of awareness on the part of the actors involved about the necessity of adapting to climate change. According to Lindgren et al. (2009), climate-related events, especially floods and storms, are already among the factors most frequently causing disruptions for railways. Despite this indication, only a few railway companies are taking serious steps to make their systems more resilient to weather extremes and changing temperatures.

1.2 Objectives and structure

This paper emerges from the EC-funded project WEATHER ("Weather Extremes: Impacts on Transport Systems and Hazards for European Regions") carried out between December 2009 and April 2012. It deals with the subject by revisiting the project's general findings on adaptation strategies and by adding two specific cases: (1) advanced winter maintenance on roads in southwest Germany and (2) technical and organizational measures in Alpine rail transport. These examples bring us closer to answering the question of how far the rising weather-related costs of the transport sector can be eased by applying suitable adaptation strategies. These case studies shall demonstrate how adaptation procedures in the transport sector can be initiated by low regret measures.

The structure of the paper is as follows: Sect. 2 starts with a brief introduction to the cost estimation and forecast methodology in the WEATHER study. The findings on current damage costs and cost developments presented focus on the regions and hazards investigated by the subsequent case studies.

Section 3 opens the main part of the paper by reviewing the analysis of adaptation strategies carried out in the WEATHER project. Next to discussions of the pros and cons of investment-based adaptation strategies versus soft measures, the section lists the top ten adaptation strategies identified in the WEATHER adaptation database and reviews the 11 European and worldwide case studies on damage cases carried out in the framework of the project.

Sections 4 and 5 continue by looking at two specific cases. Section 4 describes how road weather information systems (RWIS) are currently organized and discuss their future potential with reference to the impact of extreme winter conditions on roads in the German federal state of Baden-Wuerttemberg. Section 5 reviews the damage cost estimates of Alpine rail transport and the corresponding adaptation options discussed in various WEATHER Deliverables.

Section 6 finally summarizes the results and discusses them in a sector-specific and a broader regional context.

2 Vulnerabilities in road and rail transport

2.1 Some evidence from literature

In today's global and highly interdependent economy, supply chain disruptions are becoming more and more critical and costly (Hendricks and Singhal 2005). These can be defined as events which constrict or interrupt the flows of materials and goods in the supply chain (Wilson 2007). In particular, any disruption to the transportation system can severely harm its performance (Giunipero and Eltantawy 2004). The road transport system has proven to be one of the most critical infrastructures. In 2009, road transport volume in Baden-Wuerttemberg accounted for about 77.4 % of the total volume of transport, so that road transport is regarded as the most important transport mode by far (Statistical Office Baden-Württemberg 2011a).

A limited functioning or disruption of the road system can result in extensive consequences. Extreme winter conditions (EWCs) are among the most hazardous weather phenomena in Central Europe (EEA 2010). Experiences of past winters, especially in 2009/2010 and 2010/2011, showed that large-scale disturbances or interruptions of road transport during winter periods are a recurring risk in Germany (DWD 2011). In December 2010, for instance, the German Association of Parcel and Express Delivery Companies (BdKEP) announced that delivery could be delayed for up to 3 days due to snow and ice.

Adverse winter conditions on the roads cause road friction, visibility reduction and obstruction (Rowland et al. 2007). Furthermore, ice and snow affect vehicle performance in terms of traction and driver capabilities as well as behavior (Rowland et al. 2007). Extensive periods of ice and snow result in substantial damages to infrastructure assets (cf. FHWA 2010; cf. Doré et al. 2005). In Europe, the total annual damages of ice and snow to road infrastructure amount to 248.8 million Euros (Doll et al. 2011). Among the typical hazards of EWCs are snow and ice debris of trees, snowfall, snowdrift, ice and extremely low temperatures (Trinks et al. 2012). While the direct impacts of EWCs can be distinguished into damages to infrastructure assets, vehicles and accidents affecting health and life, their indirect impacts can be separated into infrastructure operations, user time costs and vehicle operations (Doll et al. 2011; Trinks et al. 2012). Several studies have analyzed the impact patterns of ice and snow on road transport; mostly for European and North American regions (cf. Doll et al. 2011). According to Stiers (2005), the occurrence of ice raises the number of accidents on Dutch National State Roads by between 77 and 245 %. Andrey et al. (2001) show that snow substantially increases the risk of collisions and injuries relative to dry weather control periods. For the United States, reports state that winter conditions increase the crash rate by 84 % and the injury rate by 75 % (Qiu 2007). Strong et al. (2010) found that adverse winter weather reduces traffic speeds and increases crash frequencies, while the number of fatal crashes actually decreases. Compared to seasonal dry conditions, the risk of minimal or minor injuries in Canada is 89 % higher during snowfalls (Andrey 2010). Figure 1 presents a qualitative model of the discussed interrelations between the individual hazards of EWCs and the direct and indirect impacts on road transportation.

2.2 Current vulnerability levels

The two case studies presented in this paper deal with winter impacts on roads in Germany and with the consequences of flooding on Alpine rail transport. To allow judging the relevance of these two cases in the context of the impacts of severe weather events on European transport systems now and in 40 years time, here we briefly introduce the vulnerability damage estimates and projections by the WEATHER project. We remain with reporting and discussing the results for winter impacts, embracing cold spells, snow cover and blizzards, as well as hydrological hazards including rain, floods and mass movements for the two related WEATHER climate zones mid-Europe (Germany and Benelux) and the Alpine arc (Austria, Switzerland and Slovenia) for road and rail transport. We express

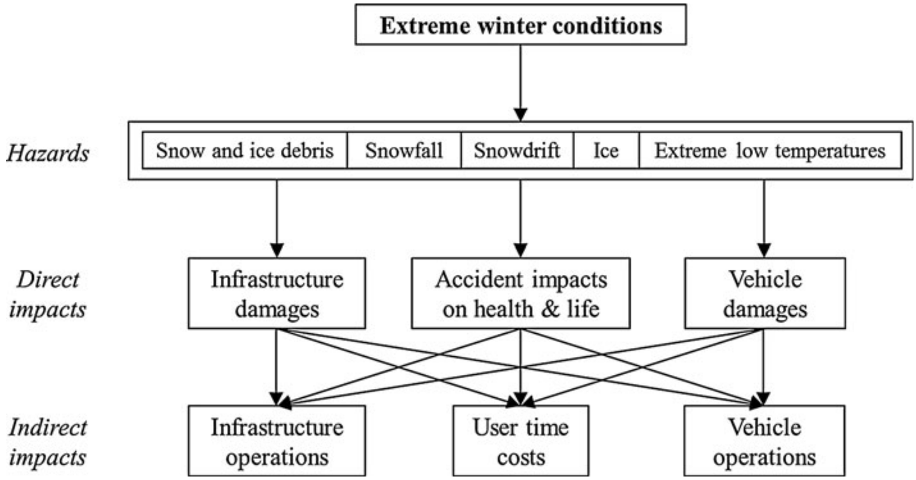

Fig. 1 Direct and indirect impacts of EWC on road transportation

vulnerability levels by total economic losses, including net infrastructure losses, servicing, user time costs and accident consequences. For methodological details, the reader is referred to the related paper by Doll, Klug and Enei in this special issue on cost estimation procedures in the WEATHER project.

In the past decade, winter and flood events accounted for 96 % of the total costs in the Alpine arc, 92 % in mid-Europe and 91 % across EUR29 (EU plus Switzerland and Norway). However, the risk profile in the two regions and transport modes looks quite different. While the road sector in mid-Europe is dominated by winter-related costs, European roads in general are slightly more affected by the consequences of floods. In rail transport, in contrast, we see a very clear dominance of floods and their consequences, including landslides, mudflows and avalanches. This is because winter mainly affects punctuality, particularly at the onset of winter, and thus longer winter periods impose an only under-proportional impact on the system after operational procedures are accommodated to the prevailing conditions. Floods and mass movements, however, have a high potential for damaging infrastructures with several months of entailed repair and detouring traffic, which is more relevant in rail than in road networks as these are less dense and much more complex to operate (Table 1).

2.3 Vulnerability projections to 2050

Transport systems have long-lived infrastructures. Road layers, rail tracks and bridges may be exchanged after a couple of decades, but their alignment as well as tunnels, cuttings or embankments remains in use for much longer. This means that the infrastructures built today will most likely still be in use at the end of the century. However, risk patterns will continue to change in the course of climate change. Both the WEATHER (Przyluski et al. 2011) and EWENT projects (Nokkala et al. 2012) have forecasted potential damages for the transport sector. For the meteorological basis, WEATHER used the EWENT predictions of extremes. Accordingly, heat spells, storm activities and hydrological phenomena will increase significantly across Europe until 2050, while winter intensities and snow cover will decline. Other factors driving the development of damage costs are changes in infrastructure assets,

Table 1 Average damage costs (€ per 1,000 pkm-eq.) 1998–2010

Category of hazards	Road transport			Rail transport		
	Mid-Europe[a]	Alpine arc[b]	EUR29 total[c]	Mid-Europe[a]	Alpine arc[b]	EUR29 total[c]
Total costs 2000–2010 (million Euros)[d]						
Winter-related	224	94	756	1.2	1.4	5.0
Hydrological	112	86	819	43	30	283
Development of total costs 2000–2010 to 2040–2050[d]						
Winter-related	−50 %	−48 %	−41 %	−28 %	−24 %	−22 %
Hydrological	22 %	39 %	50 %	60 %	79 %	75 %

Source: data from Przyluski et al. 2011

[a] Switzerland, Austria and Slovenia; [b] Germany and Benelux; [c] EU27, Switzerland and Norway; [d] infrastructure damages, operations, user time losses and accident consequences, 2010 price base

transport demand and the level of adaptation measures undertaken. Transport network and demand developments have been taken from the GHG-TransPoRD project (Fiorello et al. 2012) by climate zone and transport mode. Adaptation strategies were not considered as the cost projections shall indicate the need for adaptation rather than its result.

The forecasts indicate that expected milder winters in Europe lower the expected total costs for road transport by 50 % against a decrease in winter-related costs across Europe of 41 %. However, a lower probability of harsh winter conditions will probably reduce the level of preparedness of road authorities, which then makes the single event more costly. There is thus anyway the need for good weather warning and information systems.

The high increase in rail-related damage costs of +80 % is partly due to the high sensitivity of rail to flood and mass movement consequences and partly due to the strong increase in rail demand (+70 %) projected by the GHG-TransPoRD project. Anyway, the figures strongly suggest that adaptation of rail networks to an increasing number of hydrological events is needed, particularly in the Alpine area.

3 A more general view on adaptation strategies

In the WEATHER project, we have looked at options to adapt the transport sector to variations in climate and weather patterns between now and 2050 in two ways. First, a broad review of literature sources, interviews and workshops has provided a general inventory of adaptation options for all modes of transport, activity fields and the most relevant weather activities. Interview partners and workshop participants were selected from academia, the construction and vehicle manufacturing industry and transport undertakings. In parallel, a series of European and world wide case studies has been carried out to understand what the determinants, benefits and risks of good or bad crises management are. In the following, both levels of analysis are introduced and are eventually compared to each other.

3.1 Methodology for identifying efficient adaptation measures

The transport sector constitutes a complex composition out of expensive and partly long life infrastructures, several levels of network planning and operation authorities and a mix of public, commercial and individual users. In particular, in densely populated regions with high standard and interconnected networks and services, planning and operating transport involves several levels of decision making. Maintenance and operation contracts between federal and local governments further complicate the decision structures in most countries. In the rail sector, commercial or privatized public entities, i.e., national rail network companies together with public and private carriers, take another share of the responsibility for the design, maintenance and operation of transport networks and services. Finally, road networks and rail services are used by passenger and forwarders with their individual level of information availability, constraints and preferences.

In front of this rather complex setting of institutions, interactions and partly diverging short run and strategic goals the implementation of an all-embracing strategy to adapt the entire sector to the possible consequences of climate change and altering weather patterns appears to be challenging, if not impossible. Thus, we have focused on four activity fields, reaching from long-term and high-level policy strategies to rather short run operational decisions by service providers and users. In detail these are:

- Planning: all strategic considerations covering long time horizons, i.e., classical infrastructure and land use planning.
- Infrastructures: direct infrastructure protection, construction standards, materials, maintenance practices and emergency management procedures.
- Vehicles: measures around the design of vehicles to ensure the safety and comfort for passengers and shipments.
- Operations: activities by passenger and freight carriers to increase resilience, including staff information and training, as well as information provision to users.

For each of the four categories, we have identified suitable adaptation measures based on a literature review, sector interviews, an expert poll and a stakeholder workshop. In total, around 300 single measures have been identified and have been grouped into 62 families of measures in order to ease the complexity of interpreting the results. The groups of measures are rather evenly distributed across activity fields, with most measures found for infrastructures (22) and service operations (18).

Twenty-nine measures (47 %) are assumed to increase the resilience of transport systems across all categories of hazards. These are primarily those on improved weather forecasts, staff training, vertical integration of information flows and command and control structures, as well as on inter-modal and inter-company cooperation.

For the assessment of the measures, a multi-criteria assessment (MCA) framework has been developed and applied. We did not apply a sophisticated cost-benefit analysis because of the highly diverse nature and scale of measures and due to a lag in data availability across all climate zones, modes and activity types.

For the MCA, we have identified five assessment categories: the risk reduction potential (or benefit) of the measure, the flexibility of reacting on changing risk patterns, the feasibility and acceptability of the measures, its wider economic, environmental and social impacts, and finally its life cycle costs. For all assessment categories but the wider impacts, we defined a scale of 0–3 by which the measures are rated.

3.2 Results of the WEATHER adaptation measure assessment

Table 2 presents the ten measures ranked best by the five criteria. For readability reasons, we have decided not to plot all five criteria, but only the two most relevant, i.e., the risk reduction potential (0 = no potential to 3 = very high potential) and the costs (0 = no costs or feasible within standard maintenance cycles to 3 = very high investment and/or maintenance costs), and the total score out of all five criteria (higher score = better cost to benefit ratio).

Table 2 presents a rather diverse list out of very specific technical measures, such as locomotive equipment and nano-materials for aircraft wings, next to broad recommendations on cooperations and the internal organization of institutions and companies. But all of the measures presented have in common that no huge additional investments are required and that the co-benefits besides climate adaptation are considerable. For instance, the equipment of locomotives with modern communication technologies meeting the European Train Control System (ETCS) standard brings about higher safety levels and allows a more flexible usage of rail network capacity. The different approaches of vertical and horizontal cooperation of undertakings and institutions might increase the competitiveness and efficiency of the European logistics and passenger transport sector in total and contingency planning and staff training in companies may improve the identification of employees with their company.

The other end of the ranking is occupied by rather expensive investment measures. Among the bottom ten measures identified by the MCA approach, we find dykes and sea barriers, pavement of unpaved roads, shift of infrastructures to less risky routes or elevating buildings and key equipment. However, despite the low ranking of these measures by the MCA, in some regions with high risk levels, investments in protection systems will certainly be superior to information and organization measures.

3.3 Results of the WEATHER case studies

Within the project, we have carried out eleven case studies in Europe and worldwide. These were designed to collect experiences on damages, response, preparedness and

Table 2 Top 10 adaptation measures according to the WEATHER MCA methodology

Group of measures	Sector	Mode	Benefit	Costs	Score
1: On-board train control units compatible with latest ETCS standard (level 2/3)	Fleets	Rail	3.0	1.0	265
2: Rail couch ventilation systems for higher temperature ranges	Services	Rail	3.0	1.0	262
3: Horizontal cooperation of companies in logistics and passenger services	Services	Road	3.0	0.0	261
4: Installation of monitoring and effective user communication systems	Infrastructure	Road	2.5	1.0	249
5: Improved road pavement materials and design standards	Infrastructure	Road	3.0	1.0	245
6: Snow deflecting covers on bogies on railway rolling stock	Fleets	Rail	3.0	1.0	240
7: Nano-structured materials for aircraft wings to prevent icing	Fleet	Air	2.0	1.0	236
8: Vertical cooperation between state, undertakings and customers	Services	All	2.0	0.0	233
9: Contingency planning and awareness raising in undertakings	Services	All	3.0	1.0	232
10: Education and training of staff, clients and suppliers	Services	All	3.0	2.0	226

ECTS European Train Control System

Source: Fraunhofer ISI

adaptation strategies on the local level. The case studies covered all types of hazards and a great variety of regions and transport modes. As for some extra-European cases, namely Australia and New Zealand, multiple individual hazards had been submitted, in total 14 damage cases have been available. These were as follows:

- Floods (5 cases): Germany (Elbe) 2002, Bulgaria 2005, Switzerland 2005, Austria (rail link Vienna-Prague) 2006 and Australia (Queensland) 2010/2011,
- Hurricanes and blizzards: Italy (Alpine area) 2004, France (Xynthia) 2010, USA (Irene, New York) 2011,
- Heatwave (1 case): Germany and Netherlands (summer heat wave) 2003 and Australia (Queensland and Victoria) 2009
- Wild fires: Greece (Peleponese) 2007 and Australia (Black Saturday bushfire, Victoria) 2009

From New Zealand, reports on the Canterbury earthquake 2010 and the transport impacts of volcano eruptions had been received. The cases have reported very different levels of damages, preparedness, learning from past events and political coordination and action. The most positive examples were the handling of hurricane Irene in New York, the treatment of Lahars in New Zealand and the Swiss adaptation strategy. In all cases, the core element of good preparedness and damage mitigation was proper incident warning systems plus decisive action and clear communication strategies. The cases clearly indicate that a high level of preparedness helps preventing the most extreme impacts of natural hazards.

Figure 2 summarizes the adaptation strategies considered successful by the WEATHER case studies and international panel reports by number of cases. The measures are grouped by institutional, investment and operational adaptation strategies. Ranking these by the number of cases reveals about the same pattern identified by the general adaptation assessment framework of the WEATHER project, based on literature assessment, expert polls and a workshop.

In the selected cases, infrastructure investments are only considered beneficial in the Alpine area. However, we can suspect that in case of a different sample of study cases with a better representation of coastal, river side and mountain areas, the high benefits of constructive adaptation strategies in such areas at high risk would be emphasized. Prominent examples are the flood gates in Rotterdam and Venice or the extension of river retention areas in Germany and the Netherlands.

One of the lessions learned from the WEATHER research was that although some general patterns of good preparedness could be identified, each case study turned out to be unique on one sense or another. For discussing appropriate preparedness strategies, one thus always need to look into specific cases. The following sections therefore look into the illustrative decision situation of a road authority confronted with general winter patterns and a railway company reviewing a past damage event.

4 Case study Baden-Wurttemberg roads: the benefits of improved weather warning systems

This first case study illustrates a potential decision situation of a mid-European road authority planning for more resilience to winter impacts. This specific example was not part of the WEATHER case studies and thus provides additional information to the assessments in Sect. 3.3. The road transport system is technically far less complex than the scheduled mass transport modes rail and aviation. Basically, road travel just requires

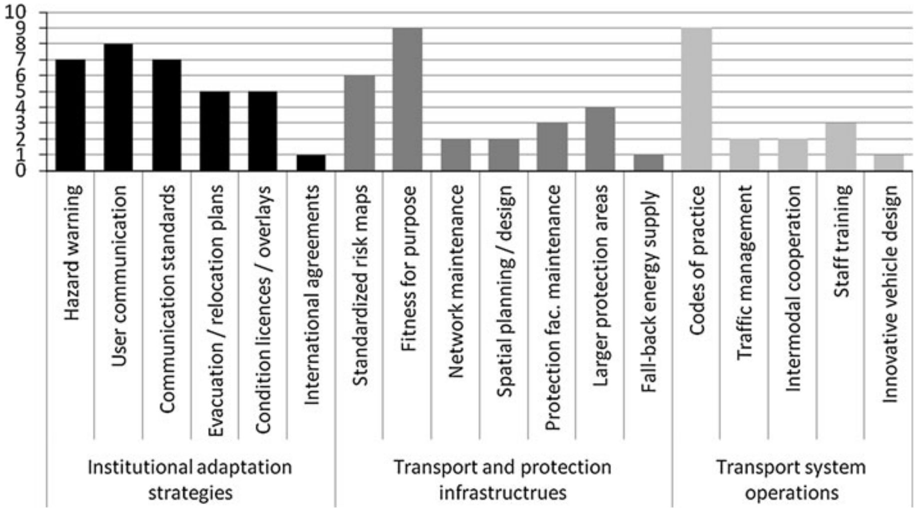

Fig. 2 Adaptation strategies considered positive by WEATHER case studies. *Source*: Fraunhofer ISI

driveways of a minimum standard, plus a set of rules communicated to the individual drivers to allow safe and comfortable travel. In this environment, road authorities take only part of the responsibility for maintaining safety and system availability under abnormal conditions. Drivers and companies, performing and planning road trips, need to be informed and prepared to react in an appropriate way. In absence of a central control unit in road transport, the relationship between public bodies and private infrastructure users can get rather complex. This section aims at shedding some light on the different players in the road sector and on promising ways to intensify their collaboration.

4.1 Investigating the direct impacts of winter conditions on road transportation in southwest Germany

This section presents findings concerning the direct impacts of EWCs on road transportation in the federal state of Baden-Wuerttemberg in southwest Germany. The conducted analysis follows the methodological approach proposed by Trinks et al. (2012). The analysis is based on the annual reviews of the German national meteorological service (Deutscher Wetterdienst, DWD), which list occurrences and consequences of weather events in Germany for every month of the reported year. The reports present information in a mostly narrative way and contain only a few quantitative details. Nevertheless, the information about EWCs during the winter periods of 2004/2005 and 2009/2010 can be used to compute the number of days for which direct impacts of EWCs on road transportation in Baden-Wuerttemberg (so-called event days ED_{EWC}) were reported. To ensure the comparability of the findings across regions with different infrastructures, the variable ED_{EWC} is expressed in days per 1,000 road km of the road network of Baden-Wuerttemberg, which has a road network length RNL of 15.383 km excluding local roads (Statistical Office Baden-Wuerttemberg 2011b). In detail, ED_{EWC} is defined as

$$ED_{EWC} = \frac{\sum ed_{EWC,i}}{RNL} \cdot 1000,$$

with

$$\mathrm{ed}_{\mathrm{EWC},i} = \begin{cases} 1, & \text{if direct impacts were reported on a day } i \text{ in the observation period} \\ 0, & \text{otherwise.} \end{cases}$$

Within the scope of the conducted analysis, the direct impacts on road transportation are considered as the physical consequences of EWCs for infrastructure, vehicles health and life. It is assumed that the indirect effects in terms of negative impacts on transport infrastructure operations (e.g., winter maintenance), vehicle operations (e.g., costs of additional fuel consumption) and user time costs (e.g., delays) are caused by the direct physical impacts (Doll et al. 2011). From a statistical point of view, extreme weather events are defined as events that occur in less than *n* % of the cases in a given observation period (cf. Zhu and Toth 2001). According to Beniston et al., extreme events can be defined along three dimensions: rarity, i.e., events that occur with relatively low frequency; intensity, i.e., events that have large magnitude deviations from the norm; and severity, i.e., events that result in large socioeconomic losses (Beniston et al. 2007). In that sense, this analysis follows a severity-based approach and takes no explicit account of the remaining criteria rarity and intensity. Thus, an event is considered as extreme if—and only if—direct impacts on the road transportation system occur and were reported in the annual reviews of the DWD (cf. Trinks et al. 2012). Due to the limited case numbers, a sound statistical analysis was not feasible and only highlights of the quantitative findings are discussed.

The analysis of the DWD statistics reveals that direct impacts of EWCs on road transportation were reported for 118 days in Baden-Württemberg in the six winter periods between 2004 and 2010, resulting in an average of approximately 20 event days per winter period (Fig. 2). The average figure of $\mathrm{ED}_{\mathrm{EWC}}$ across all six winter periods is approximately 1.3 event days per 1,000 road km. $\mathrm{ED}_{\mathrm{EWC}}$ peaked at 2.21 in the winter period 2004/2005. In contrast, the remarkably low figure of 0.07 was derived for 2006/2007. Thus, $\mathrm{ED}_{\mathrm{EWC}}$ has a considerable range of 2.13 event days per 1,000 road km within the observation period.

The findings presented are, however, subject to various limitations and uncertainties which need to be taken into account. Since the annual reviews are based on newspaper reports, the quality of the results depends on the objectivity and completeness of the media coverage. Due to the tendency of newspapers to over-report spectacular events (Solvic 1987), it is conceivable that regional events or events impacting the economy rather than the population are overlooked (cf. Trinks et al. 2012). Due to the lack of basic evaluation criteria for the impacts, it is likely that reports under- or over-represent relevant events (Trinks et al. 2012). By definition, EWCs are connected to damages and incidents and not to extreme events in meteorological terms. In that sense, an even moderate winter may lead to more trouble to the transport system than a meteorological more extreme one. Therefore, the possibility to explain the observed trends in Fig. 3 with reference to meteorological extreme conditions in those years is diminished. Finally, hidden factors, such as learning effects or increasing vulnerability, cannot be investigated by the analysis (Trinks et al. 2012). Although the analysis is limited to just a small snapshot, the range of $\mathrm{ED}_{\mathrm{EWC}}$ found and illustrated in Fig. 2 is relatively large and hints at the fact that EWCs can vary substantially from period to period.

4.2 Extreme winter conditions and climate change in southwest Germany

During the course of climate change, the patterns of winter conditions in Baden-Wuerttemberg will undergo substantial changes. First, due to higher temperatures, warmer winter

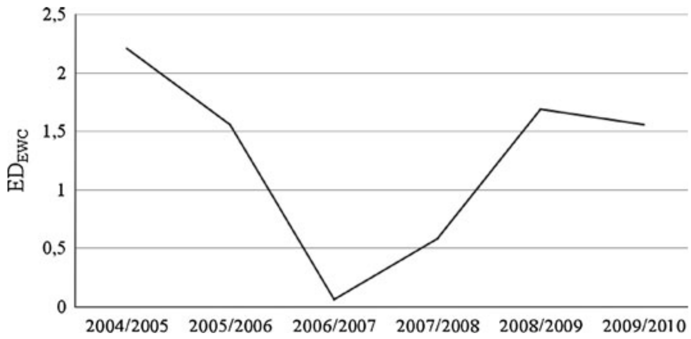

Fig. 3 ED_{EWC} between 2004/2005 and 2009/2010 for road transportation in Baden-Wuerttemberg. *Source*: Data from DWD (2011)

periods with 25–65 % fewer snow days are expected until the middle of the twenty-first century (UVM and LUBW 2010). In the Rhine Valley, for instance, 10 frost days less per year are expected on average for the period 2011–2040 (UVM and LUBW 2010). For the same period, a 35 % increase in precipitation (rain) in winter is predicted until 2050 (UVM and LUBW 2010). Beyond these trends, the greatest challenge of climate change that lies ahead in terms of assessing EWCs' impacts on road transportation is the increase in volatility and uncertainty (cf. Love et al. 2010).

Love et al. (2010) consider it essential to monitor transportation systems in order to detect and quantify climate change vulnerabilities as well as improve the effectiveness of adaptation strategies. To this end, RWIS make an important contribution, because they (1) facilitate the long-term monitoring of climate change in EWCs' impacts on road transportation and (2) contribute directly to the mitigation of risks (e.g., road crashes) by providing real-time warning about crucial weather conditions to road transportation stakeholders (Papanikolaou et al. 2011; Andrey et al. 2001).

4.3 Installation of road weather information systems as an adaptation strategy

IPCC (2001) defines adaptation as 'adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.' Since the consequences of climate change for transportation systems are increasing slowly and are highly uncertain, one of the main adaptation challenges is to avoid non-targeted measures through so-called no-regret options (Love et al. 2010; Hallegatte 2009). No-regret adaptation is understood as a strategy that provides benefits even in the absence of climate change impacts (Hallegatte 2009). In contrast to no-regret options, other adaptation measures focus explicitly on mitigating climate change effects on road transport, such as the usage of polymeric pavement materials and fiber-reinforced concrete overlays (Doll et al. 2011).

For several reasons, the installation of RWIS can be considered a 'no-regret' option. In fact, the installation of RWIS is despite its emergency response character a long-term effort which needs to be accompanied by substantial modifications of procedures, equipment and organization. A RWIS consists of sensor stations, communication network, weather and pavement temperature modeling, tailored weather and pavement temperature forecasts, traveler information and maintenance decision support systems (Boon and Cluett 2002). Road weather station (RWS) equipment in Europe can be divided into general and specialized sensors (PIARC 2008). General sensors measure key road weather factors such as air temperature, relative humidity, road surface temperature, wind direction and speed, and the occurrence of precipitation (PIARC 2008). In contrast, specialized sensors, including video cameras, generate more specific data, such as visibility, road depth temperature, road surface conditions (state), road surface freezing point, radiation, type of precipitation (classification), dew point, snow depth on the road surface and the intensity of precipitation (PIARC 2008).

Concerning the benefits irrespective of monitoring climate change, a RWIS assists road maintenance management in terms of less salt for gritting, less environmental burdens on, e.g., ground waters, improved safety and more efficient and better targeted deicing operations (Leviäkangas and Hietajärvi 2010). A fully deployed RWIS enables the reduced use of routine patrols, cost-effective allocation of resources and providing road users with better information (Boon and Cluett 2002; Andrey et al. 2001). Thus, RWIS makes it possible to shift traditional reactive road maintenance to a more proactive approach (Boon and Cluett 2002). Besides the benefits for road maintenance management, a RWIS also has positive effects on safety in terms of driving behavior and improves pre-travel information (Papanikolaou et al. 2011; Schirokoff et al. 2005; Skarpness et al. 2003; Andrey et al. 2001; Rämä 2001; Kyte et al. 2001; Cooper and Sawyer 1993). Although RWIS are predominantly installed to monitor winter conditions and support winter maintenance, the sensors can also monitor relevant parameters of other weather events that will become more important as the impacts of climate change are felt. In spite of the wide variation of the cost–benefit ratio in the studies, the benefits summarized in Table 2 always outweigh the costs.

4.4 Risk reduction due to improved road maintenance

RWIS cannot offer protection against the deterioration of infrastructures as the sudden consequence of weather extremes, such as floods, heat or cold spells. But they do help to address one of the most costly consequences of these events: system performance in terms of user time losses and safety. It is highly probable that information and communication systems will be greatly expanded in the decades to come in all aspects of transport, including road network operations. “The large co-benefits of road weather information systems (RWIS) imply that they will be improved anyway, with or without the visible consequences of climate change in Europe” (WHO 2010). This finding confirms the general pattern of good adaptation strategies unveiled in Sect. 3: Well-planned information and communication platforms are key to efficient crises management.

In the current damage projections of the WEATHER project, we have not explicitly included the improvement of IT systems in road network management. Thus, the results suggest that the costs of road network operations, user time and safety decline to some extent by 2050. In addition, we need to acknowledge that new road construction materials and in-vehicle safety technologies will add other benefits, so that a considerable share of the climate impacts on road transport can be mitigated by new technologies and operational procedures (Table 3).

5 Case study Austrian railways: the benefits of investments and operational improvements

This second case study focuses on decision processes and adaptation options for the rail transport sector in general and with a specific focus on the Alpine region. In this sense, it

Table 3 Benefits of RWIS

Issues	References	Identified impacts
Winter road management, maintenance and operations	Ye et al. (2009)	Positive impacts of weather information system on winter maintenance costs (cost/benefit = 8)
	Boselly (2001)	RWIS are profitable investments (cost/benefit = 5)
	Wass (1990) and Thornes (1990)	Improved weather information will reduce winter maintenance cost by 5–30 %
	Kempe (1990)	50 % less salt for deicing with more advanced road weather information systems
	Lähesmaa (1997)	Investments in weather-controlled winter road management systems not automatically profitable (cost/benefit = 0.5)
	Pilli-Sihvola et al. (1993)	Road weather service is beneficial (cost/benefit = 5)
Other road management, maintenance and operations	Skarpness et al. (2003)	Weather information portal found very useful by road management personnel and road users
Safety effects in winter conditions	Rämä (2001)	Variable message signs (VMS) reduce speeds (1.2 km/h on average) and result in accident avoidance
	Schirokoff et al. (2005)	A wide-scale adoption of VMSs would enhance safety impacts and an aggregated system would have a cost/benefit of 1.4
Safety effects in general	Cooper and Sawyer (1993)	Fog warnings by VMSs reduce speeds and improve safety
	Kyte et al. (2001)	VMSs warning drivers about poor road weather conditions had an additional marginal impact on driver behavior reducing speeds

Source: Adapted from Leviäkangas and Hietajärvi (2010) turns toward the rather critical regions most likely requiring more investments than suggested by the previous case study. This case study was part of the WEATHER project and thus added to the findings of Sect. 3.3. As a first step, the vulnerability of the rail system is assessed, which then leads to a discussion of possible adaptation options and their benefits, applicability, side effects and costs. To convey the general findings of the WEATHER project as well as the special case of the Alpine arc, the vulnerability assessment and the adaptation options are discussed for both Europe and the Alpine region.

5.1 Rail system vulnerability

This section examines the vulnerability of the rail system to each extreme weather event. Table 4 gives an overview of the most relevant possible impacts of the different extreme weather events and their impact level for a wide variety of technical and organizational elements of the rail system. This assessment can differ (slightly) between European regions, such as coastal zones, mountainous areas or Nordic and Mediterranean regions.

In addition to the regional differentiation, the impacts differ according to the type and especially quality of infrastructure and its maintenance (Baker et al. 2010). The worse an infrastructure unit is maintained, the higher the risk of damage and/or closure (due to safety reasons). The better an infrastructure is adapted to various and changing weather conditions caused by climate change, the lower is the risk of damage and/or closure (due to safety reasons). Therefore, not all the costs caused by a weather event can be allocated to this weather event. Some of the costs are due to inadequate maintenance of infrastructure or its systems of protection (Enei et al. 2011).

Vulnerability also depends on the habituation of regions to specific events. The more often specific events occur, the better the infrastructure is equipped to handle these events. This applies especially to those events relevant for the Alpine region (floods, landslides and avalanches, harsh winters with prolonged and intensive frost periods) (Enei et al. 2011; Maibach et al. 2012).

The described vulnerabilities associated with extreme weather events lead to different kinds of costs, including infrastructure damage, infrastructure operation or user costs (Doll et al. 2010). The bandwidth of these costs depends on the weather event itself, the type of infrastructure affected, the degree of usage of infrastructure and the infrastructure conditions.

The length of infrastructure affected and how long it is closed have a major influence on the costs incurred. Therefore, the average costs of track closure per day and section and the average infrastructure damage costs per km are relevant indicators for estimating the costs of future extreme weather events in the rail transport system (Table 5).

Key focus of this paper is adaptation strategies for transport infrastructure. Therefore, refer to the deliverables of the WEATHER project (Sedlacek and Pelikan 2011 and Enei et al. 2011) for detailed information on cost calculation procedures.

5.2 Adaptation options for the rail system

Based on the literature as well as expert assessments given during the WEATHER workshops and interviews, the project team developed an extensive list of possible adaptation measures to protect infrastructure against extreme weather effects and therefore to reduce costs (for infrastructure assets, operation and usage) (Doll et al. 2011). The compiled strategies revealed that almost all the suggested adaptation measures are state of the art for new rail infrastructure assets in those European regions, where such measures

Table 4 Vulnerability of the rail system to extreme weather events

	Temperature			Precipitation			Wind		Consequent events			
	Without consequent events listed on the right											
	Heat periods	Frost periods	Extensive fog	Rain falls	Snow	Drought	Storms	Storms surges	Wild fires	Floods/flash floods	Landslides/ mudflows	Avalanches
Infrastructure												
Basement	0	~	0	~	~	~	0	~	0	X	X	X
Rail track	~	~	0	~	~	0	0	~	X	X	X	X
Safety and other equipment	0	~	0	0	0	0	~	~	X	X	X	X
Catenary and lightning	0	~	0	0	0	0	X	X	X	X	X	X
Buildings	0	0	0	0	0	0	X	X	X	X	X	X
Operation												
Closure of track (damage)	~	~	0	~	~	~	~	X	X	X	X	X
Closure of track (safety reasons)	~	~	~	0	X	0	X	X	X	~	0	X
Derailment	X	X	0	0	~	0	X	X	~	~	0	0
Direct hit trains	0	0	0	0	0	0	~	~	~	~	~	~
User												
Time loss passenger	~	~	~	~	X	~	X	X	X	X	X	X
Increased travel costs passenger	0	0	0	0	~	0	X	X	X	X	X	X
Time loss freight	~	~	~	~	X	~	X	X	X	X	X	X

Source: Enei et al. (2011)

X, High influence of the weather event

~, Medium influence

0, Hardly any influence

Table 5 Unit costs for calculating impacts in rail transport

Average replacement costs per affected network-km (million Euros/km)	Average replacement capital costs per affected network-km (million Euros/km)	Average additional service costs and revenue loss per day and affected network section (Euros/day/section)	Average additional user costs per day and affected network section (Euros/day/section)
2.55	0.13	43,600	27,700

Source: Enei et al. (2011)

are already regarded as essential to protect infrastructure against specific weather events. Only measures which are not promising or which have high implementation costs were not yet used, such as the replacement of rail overhead wires by a power supply integrated into the track, because this would mean a system change for the whole electrified network and costs that would exceed the expected benefits (Doll et al. 2011).

This leads to the conclusion that the future implementation of measures does not depend so much on technology development, but rather on political decisions. Political decisions, in turn, depend to a large extent on the available public budget which is becoming more and more restricted. Finally, whether adaptation strategies are implemented and maintained consequently also depends on the mix of measures chosen and their acceptance by the general public, by stakeholders as well as by politicians.

Therefore, it is important to select measures which are affordable and have a political benefit. This leads to the necessity to create a marketing concept for each important and beneficial measure for every stakeholder involved.

Based on a literature analysis, additional information from the 3rd WEATHER workshop in Rotterdam 2011 and a series of interviews with rail infrastructure experts, the most promising measures were selected. It was also taken into consideration whether the identified measures belong to the category of *no-regret options*, i.e., whether they would be implemented anyway by 2050 for reasons other than adapting to extreme weather events. They include the following measures:

- Switch protection (Doll et al. 2011)
- Pile construction for buildings with technical equipment (Maurer et al. 2012)
- Cooling of signals and installation of fans to keep electronic equipment functional during periods of extreme heat (Hoffmann et al. 2009)
- Increased (preventive) maintenance activities (infrastructure and existing protection systems) (Lindgren et al. 2009; Regmi and Hanaoka 2009)
- Vegetation management along rail tracks (Lindgren et al. 2009; Maibach et al. 2012)
- Installation of (automatic) monitoring systems (Lindgren et al. 2009; Baker et al. 2010)
- Incentives (for responsible stakeholders) and regulations to apply and maintain adaptation measures (e.g., voluntary integration of adaptation measures into cost-benefit analysis for new infrastructure) (Maurer et al. 2012)
- Land use regulations (Lindgren et al. 2009; Maibach et al. 2012).

Not all of the above measures are relevant to mitigate the impacts of hydrological and winter damages in mountain areas like the Alps. The most important measures for the Alpine region are switch protection, increased (preventive) maintenance activities (infrastructure and existing protection systems), vegetation management along rail tracks and installation of (automatic) monitoring systems. These options are discussed in detail in the following subsections:

1. Protection of switches

Major rail system problems in winter occur due to the malfunctioning of switches due to frost and snow. Countries in Alpine regions and Scandinavia have already started to introduce protection such as heating, covers or brushes. Every railway network has a huge number of switches (on average about 200–400 switches per 100 km network), which makes their protection costly and time-consuming.

To prevent increased CO_2 emissions (due to an increase in the power supply), new heating systems are being developed and are already partly in operation. These systems work with alternative heating technologies (use of geothermic energy) that reduce electricity consumption. This helps to lower the operating and user costs of extreme winters.

2. Increased (preventive) maintenance activities (infrastructure and existing protection systems)

Too little maintenance and too late renewal of infrastructure are important reasons for the bad condition of parts of the rail infrastructure. However, maintenance measures are very flexible to changes and future needs. In general, it is easy to implement optimal maintenance because the theoretical knowledge exists and good practices in some countries and for some high performance railway networks show what can be done in this regard. In the short run, maintenance costs may be regarded as high, but good maintenance extends the infrastructure's useful life and therefore reduces life cycle costs in the long run—this leads to positive economic effects for future generations.

3. Vegetation management along rail tracks

Which kind of vegetation is best suited to rail infrastructure depends on the region and the hazards the infrastructure is exposed to. In Alpine regions, protection forests (against avalanches and mudflows) are especially relevant.

The benefits can be high, because in some cases uncontrolled or inadequate vegetation is the main reason for damages to parts of the railway infrastructure and the closure of tracks. Planting-specific vegetation is quite inflexible to future changes due to the long growing time of forests and other vegetation. This is especially true for protection forests in Alpine regions.

4. Installation of (automatic) monitoring systems

Monitoring systems can support maintenance measures by providing information about when and where operation problems occur—due to missing maintenance or damage by specific weather extremes. Monitoring is partly possible using automatic or semi-automatic monitoring systems, but specific monitoring is still only possible manually. However, manual monitoring is time- and cost-intensive, so that it tends to be done only sporadically. Thus, continuously operating automatic systems are better suited to identifying malfunctions in time.

5. Land use regulation

Risk maps indicate where construction bans are imposed or special construction codes have to be complied with in highly exposed areas. In the Alpine region, such high risk areas are more prevalent than in flatter environments. It is essential to consider existing risk maps when planning future rail and road infrastructures.

5.3 Risk reduction from advanced rail operations and technologies

Although the analyses have not uncovered fundamentally new adaptation pathways and technologies, it can be conclude that adaptive maintenance has great potential to mitigate the impacts of rain, floods, snow and ice on infrastructures and railway operations. For the Alpine area, it can be generalized that the largest cost block identified for the rail sector relates to system operation and users due to persistent rainfalls with consequent flood and landslide events. Here, the increased maintenance of rail infrastructures will not have significant benefits, but the increased maintenance of already existing flood protection systems as well as an optimized vegetation management can help to reduce the negative impacts of extreme weather events on the rail system.

Based on the selected cases of weather extremes in Alpine rail networks, effective adaptation measures are either very expensive or will only partly help to mitigate the strongly rising weather-related damage costs of the railways. But in order to maintain highly reliable services as is the objective of Austria and Switzerland, there is often no alternative but to invest in proper protection infrastructures. In these cases, the general statement of the superiority of institutional over investive adaptation elaborated in Sect. 3.3 does not hold true. However, the costs are lower in large networks in less mountainous countries where long-lasting extremes, such as persistent rainfalls or durable cold spells, account for a higher share of total damages. Here, improved maintenance and servicing could be efficient measures to decrease future climate-related cost burdens.

6 Conclusions

Recent research by the projects WEATHER and EWENT showed that weather impacts can cause major problems for transport infrastructure maintenance and system operations. In the European context, hydrological events and winter consequences constitute the most significant threats, having caused more than 90 % of costs over the past decade. Most vulnerable are roads due to their dominance across all transport markets and railways with their expensive infrastructures, high safety standards and system-related restrictions in reacting on disruptions in a flexible way. Further, risks increase with infrastructures in mountain areas and of low maintenance standards.

When looking three to four decades ahead, we receive a mixed picture. While harsh winter conditions will decline, the threat caused by hydrological events will grow in most regions of Europe due to a concentration of rainfall activities and higher temperatures in winter months. However, the forecasts do raise some generally relevant issues for the two case studies. In the case of winter maintenance on roads in southwest Germany roads (case study 1), we see that the costs for road operators will most likely decline. But at the same time, we must take into consideration that the declining frequency of harsh winter weather reduces the preparedness of the authorities and thus costs are increased if bad winters do occur. In this special case, improved weather information systems can help to reduce the cost burden for local, national or private road operators even further. The obvious co-benefits of improved information and communication systems often justify their installation.

There seems to be a larger adaptation potential in road transport than in rail because the road sectors' lower degree of coordination and the greater autonomy of the network users still provide room to develop intelligent monitoring, communication and control structures. Technology can improve the coordination of institutions and provide users with the relevant information in real time. RWIS are a good example, which can be expected to be greatly expanded throughout the coming decades due to advances in weather forecasting and due to the systems' other broad benefits beyond the impacts of climate change. Given that car-to-car and car-to-infrastructure communication technologies are expected to enter the market in the coming decades and will be connected to weather information systems, we can expect that large parts of the projected cost burden for road transport can be mitigated by 2050 and beyond.

In the Austrian railway case study, we have identified improved network maintenance as a more cost efficient way to reduce future damage risks, which can be realized in short to medium run. These include the regular inspections of embankments, soil structures or protection forests and strict vegetation control. Clear rules about the quality of networks as formulated in the German 'Quality and Financing Agreement for the Federal Rail Network' could help to standardize and improve maintenance processes. Such regulations could also contain clauses on the level of preparedness of the networks concerning external impacts, including sabotage or force majeure.

However, as the "low-hanging fruits", namely information and communication systems, seem to have already been harvested in the rail sector, investments in advanced protection systems, e.g., tunnels, protection walls and enlarged drainage, need to be considered to support proactive maintenance strategies. Given that the Alpine arc constitutes Europe's major freight corridor, the currently completed, ongoing and planned rail base tunnels Simplon/Lötschberg, Gotthard and Brenner not only accelerate rail travel, but also help to make the infrastructure less vulnerable to natural hazards.

The examples of hydrological events with regard to Alpine railways and the impact of extreme winter conditions on roads in southwest Germany are illustrative and do not permit a generalization to be made for all adaptation options in road and rail across all weather categories and European regions. A more general picture is given by the WEATHER project (Doll et al. 2011). Here, data analyses and case studies across Europe and worldwide revealed that it is extremely difficult to quantify the benefits and costs of adaptation measures in transport. This is partly due to the large coverage of transport networks, involving widely diverse local specificities. Cost-benefit analyses therefore need to be performed on a case study level rather than at the European level or even the level of individual countries. A proper method for quantifying costs and cost–benefit ratios of adaptation methods first has to solve the challenge of recording costs and benefits across several sectors, e.g., transport, housing, energy supply, or within the transport sector, e.g., reduction in weather-related disruptions versus generally enhanced system capacity.

Despite these methodological difficulties, the review of several cases inside and outside Europe have revealed that good applications of common emergency strategies, e.g., well-prepared emergency plans and communication protocols, are needed more urgently than the development of new technologies. However, our case study review has also shown that this general rule has some rather prominent exceptions. In mountain areas or regions close to sea coasts or river banks, organizational preparedness alone will not suffice. The danger of melting glaciers and permafrost, intensifying rain periods or rising sea levels calls for possibly expensive protective infrastructures in these regions. These may include tunnels, protection walls, dykes, sea gates, retention areas or even the re-routing of existing roads and railway lines.

On the basis of our results, we conclude that priority should be given to strengthen vertical and horizontal information channels between authorities, the transport industry and their customers. In parallel, the establishment of risk maps and reliable weather warning systems, which are accessible by the various actors, should be carried on. Thirdly, the consideration of construction measures is to be started by reviewing current building codes and adapting them to likely changes in weather and climate activity. As materials, technologies and demand levels change, the review of construction manuals and codes of practice is a continuous process which, at no time, can be concluded definitively.

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