Rethinking transport
27–30 April 2020

TRA 2020 HELSINKI

Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland

Assessing and enhancing resilience to extreme weather for transport infrastructure in Germany

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Abstract

Transport infrastructure is exposed every year to different kinds of risks and disruptive events caused by natural hazards which can permanently impair its availability and safety. In order to maintain the functionality and operation of transport infrastructure during and after an extreme weather events, appropriate methods and concepts are required which enable a holistic, conceptual and systematic assessment of system resilience. This paper presents current results from the investigations by departmental research facilities and executive agencies in the “BMVI Network of Experts”, which was initiated in 2016 by the German Federal Ministry of Transport and Digital Infrastructure (BMVI). New concepts and methods have been developed to quantify the availability and safety of transport infrastructure elements and to and enhance transport resilience to extreme weather. By providing measures and practical guidelines to prioritise them, operators will be supported in improving the performance of transport infrastructure under unfavourable weather conditions.

Keywords: transport infrastructure; resilience; extreme weather; availability; safety; critical infrastructure

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1. Introduction

Providing a safe and reliable transport infrastructure and an efficient traffic management to ensure safe operation and high availability are essential prerequisites for sustainable mobility and economic growth. These requirements present a major challenge for operators and owners of today's transport infrastructures. Considering the growing demand for mobility in our society, the progressive ageing of numerous infrastructure elements, but also the increasing complexity of infrastructural, technical and organisational aspects, these tasks are becoming increasingly demanding.

The aim is to guarantee the future reliability of German transport infrastructure, to prioritise measures and to use resources as efficiently as possible (BMVI 2017). For this purpose, methods are needed to make the reliability of transport infrastructure measurable. The performance of transport infrastructure is not only affected by structural issues at normal conditions but also by external factors such as extreme weather events. This work is focused on availability und safety of transport infrastructure during disruptive events caused by natural hazards. There are suggestions on how to make availability of transport infrastructure measurable, e.g. by the ratio of traffic intensity to capacity, but there is currently no general and consistent approach for assessing and forecasting availability and safety of transport infrastructure during unplanned and undesired events (Henseler, 2017; Thoma et al., 2016; Anastassiadou et al., 2016; Mattsson et al., 2015; Kermanshah et al., 2014).

As part of the research subtopic "Availability and safety of transport infrastructure during disruptive events" within the BMVI Network of Experts, four departmental research institutions and executive agencies of the German Federal Ministry of Transport and Digital Infrastructure (BMVI) are working together on availability and safety analyses as well as predictions: the Federal Highway Research Institute (BASt), the Federal Waterways Engineering and Research Institute (BAW), the German Meteorological Service (DWD) and the Federal Railway Authority (EBA). The aim of the co-projects presented here is to develop new concepts to quantify the availability and safety of transport infrastructure elements in order to assess and enhance transport resilience to extreme weather. For this purpose, the concept of vulnerability is applied among other approaches. A holistic resilience approach is used taking also into account the element's function in the transport network and possible mitigation measures. Moreover, weather forecasting of extreme events is improved and used in the development of new measures to increase the reliability of transport infrastructure during extreme weather. In order to determine and improve reliability, not only transport routes and civil engineering structures themselves are analysed, but also rules and standards according to which they are designed and operated.

This paper shows the latest results of our ongoing collaboration. First, the structure of the BMVI Network of Experts is presented to explain how the different agencies work together. Then, important terms are defined and our methods and results are explained in detail, followed by a conclusion and an outlook on future research.

2. The BMVI Network of Experts

In 2016, the German Federal Ministry of Transport and Digital Infrastructure (BMVI) together with federal research institutions belonging to the BMVI initiated a new format of departmental research in form of a Network of Experts entitled "Knowledge – Ability – Action". Seven departmental research facilities and executive agencies of the BMVI jointly address urgent transport infrastructure problems through innovations in their adaptation to climate change, their environmentally sound design and their reliability.

The intention behind the BMVI Network of Experts is to place existing competencies on a broader common basis, to connect the research facilities and agencies more closely and thus to promote knowledge and technology transfer. The aim is to intensify the dialogue between experts from science and research, industry and business as well as politics and administration. In this way, the BMVI Network of Experts establishes a strong link between research and practical application. It involves all relevant actors and necessary resources in order to pool expertise and skills, develop new collective research approaches and innovative problem-solving methods and adopt a cross-modal perspective (BMVI 2017).

The collaborating institutions are:

- Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BASt)
- Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde, BfG)
- Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau, BAW)
- German Meteorological Service (Deutscher Wetterdienst, DWD)
- Federal Office for Goods Transport (Bundesamt für Güterverkehr, BAG)

- Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH)
- Federal Railway Authority (Eisenbahn-Bundesamt, EBA)

Their competencies and resources are initially grouped into three topics: “Adapting transport and infrastructure to climate change and extreme weather events”, “Designing environmentally friendly transport and infrastructure” and “Increasing the reliability of transport infrastructures”. Additional topics that will be investigated more intensively in the future are “Consistently developing and using digital technologies” and “Enhanced development of renewable energy in transport and infrastructure”.

Within the research topic “Increasing the reliability of transport infrastructures”, four subtopics are investigated: “recording and assessing the condition of civil engineering structures”, “evaluating the reliability of civil engineering structures” (deterioration processes and risk management), “analysing and predicting the availability and safety of transport infrastructure for disruptive events” (from an object and network perspective) as well as “developing construction and maintenance measures to be carried out during operation”. The work presented here is part of the third subtopic “Availability and safety of transport infrastructure during disruptive events” and Fig. 1 illustrates the interconnection between the four co-projects and the collaborating institutions in this subtopic.

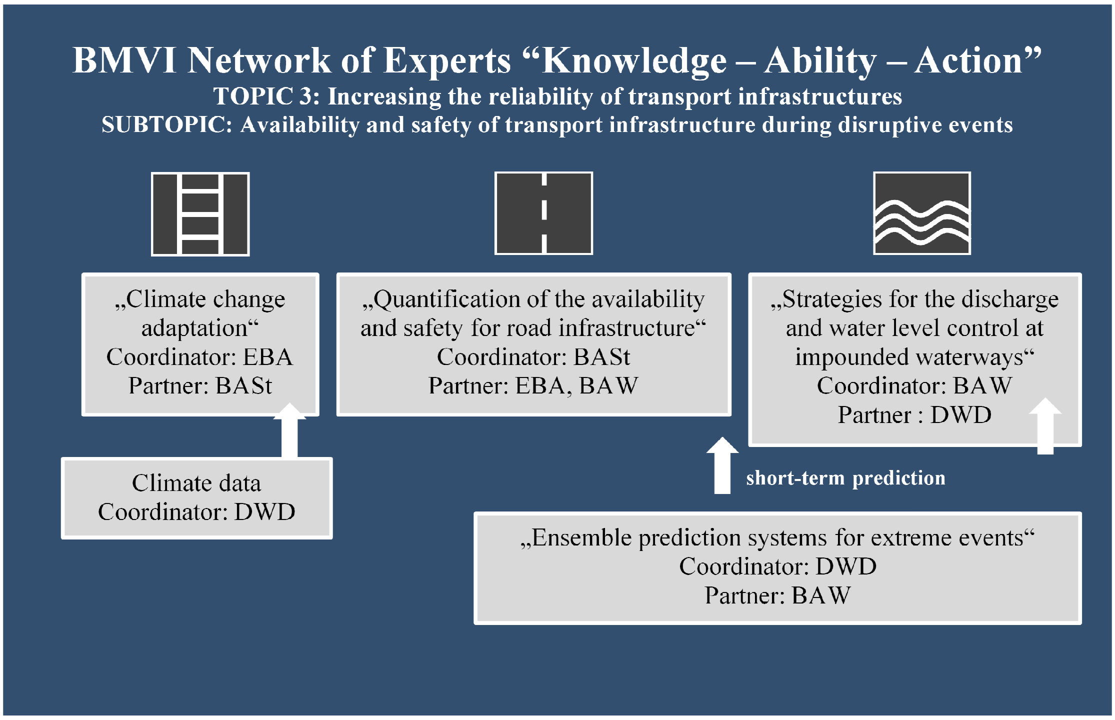


Fig. 1 Schematic illustration of the interconnection between the co-projects and the institutions in the subtopic “Availability and safety of transport infrastructure during disruptive events”

3. Terms and Definitions

Technical terms can have differing meanings in the various departmental research facilities and executive agencies of the BMVI. For a successful work on the subtopic “Availability and safety of transport infrastructure during disruptive events” it is therefore necessary to specify separate definitions of important terms and their relationships. They are given in Table 1. Bakker et al. (2010) have derived definitions from international standards and adapted them to the field of transport infrastructure.

Table 1. Definition of terms

availability	The probability that the required function can be performed at any point in time under given conditions. This corresponds to the fraction of the time that the required function can be performed under given conditions. Bakker et al. (2010)
disruptive event	Man-made, natural or technical caused catastrophes or changing processes with catastrophic consequences. Scharte et al. (2014)
extreme weather events	Storm (storm, thunderstorm, hail, tornado and dust storm), cold spell, cold wave, warm spell, heat wave, precipitation (heavy rainfall, heavy snow), flooding, drought, land- and snow slide, as well as wildfire. The warm- or cold spell is a period of abnormally warm- or cold weather. To define these events, a sequence of one week has been considered in which the temperature anomalies exceed +6°C or are below -6°C (reference period 1981-2010). For the heat or cold wave definition, besides the above conditions, the criteria of temporal scale and intensity still must be fulfilled. (DWD, 2019)
hazard	A potential source of a failure. Smith (2001)
maintainability	The probability that maintenance activities can be carried out within a given period of time, under given circumstances, to be able to (continue to) perform the required function. Bakker et al. (2010)
reliability	The probability that the required function will be performed under given conditions for a given period of time. Bakker et al. (2010)
resilience	"*Resilience* is the ability to repel, prepare for, take into account, absorb, recover from and adapt ever more successfully to actual or potential adverse events. Those events are either catastrophes or processes of change with catastrophic outcome which can have human, technical or natural causes." Scharte et al. (2014)
resilience measures	Resilience measures are understood to be those technical, planning and organizational measures on the individual structure or for the entire infrastructural network that exceed the specifications of regulatory texts in force (standards, design, codes etc.) (Deublein et al., 2019)
safety	Freedom from unacceptable risks in terms of harm to persons. Bakker et al. (2010)
vulnerability	Describes the degree to which an element of the transport infrastructure is vulnerable to disruptive events that lead to impairment or failure of its ability to function. It is a function of the nature and intensity of the event to which a system is exposed, its sensitivity and adaptive capacity. *BBK (2009)*

The given definitions refer to the current state of the studies and may be adapted as work progresses. Above all, they should be discussed and where possible harmonised throughout the BMVI Network of Experts in order to improve communication and co-operation between the executive agencies.

4. Results and Discussion

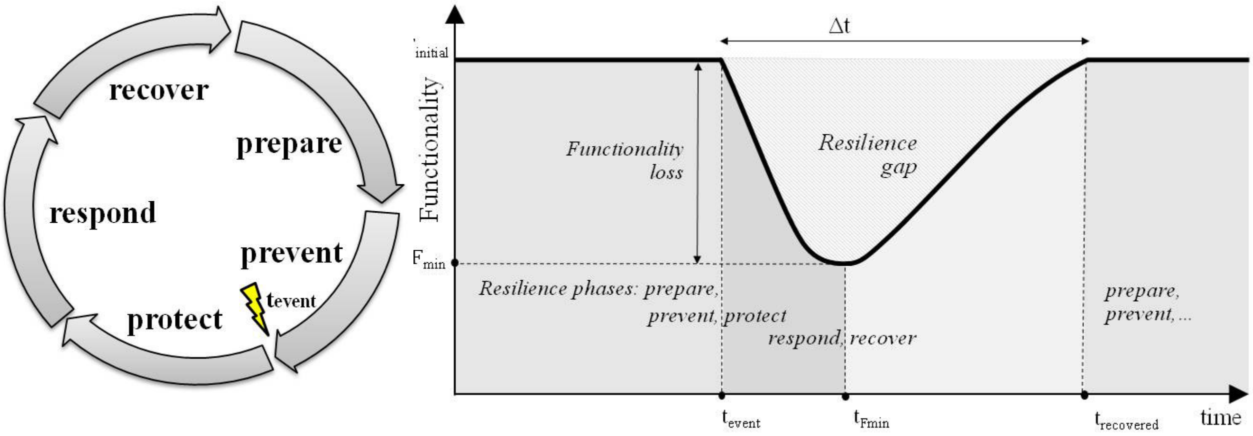
In this section, different approaches to assess and optimise transport infrastructure resilience to extreme weather, applied by the involved departmental research facilities and executive agencies of the BMVI, are presented in detail in this chapter.

4.1. Assessing and optimizing road infrastructure resilience

The vulnerability of transport infrastructures to disruptive events is growing. A major challenge for decision-makers in infrastructure management therefore lies in dealing with interruption and damaging effects on the system caused by disruptive events. To maintain or restore as quickly as possible the functionality and operation of an infrastructure system after such an event, suitable methods and concepts are required which enable a holistic, conceptual and systematic assessment and prognosis of the functionality of the road infrastructure in order to identify and prioritise target-oriented measures.

The German Federal Highway Research Institute (BASt) provides expert opinions, consultancy and research relating to road infrastructure including structural technology and foundation engineering, as well as operation and civil security aspects. This paper presents the first results of the implementation of resilience engineering to road infrastructure in order to verify the adequacy of this approach for the evaluation and optimisation of safety and availability of road infrastructure during extreme weather events. For this purpose, it is particularly important not only to identify vulnerabilities of the structures, but also to consider their regeneration times up to partial or complete recovery. Essential component of this assessment is the quantification of the resilience and the vulnerability at different levels (object and network level) in order to predict the infrastructure behaviour during the presence of an extreme event.

The resilience of a system can be assigned to five different sequential phases (prepare, prevent, protect, respond and recover) represented in the form of a resilience cycle in Fig. 1 according to Thoma et al. (2014).



(a) (b)

Fig. 1 (a) Resilience cycle in line with Thoma et al. (2014) and (b) Quantification of the resilience according to the functionality loss of the system on basis of Deublein et al. (2019)

Based on Bruneau et al. (2003), the loss of resilience (resilience gap) shown in Fig. 1(b) can be described mathematically as follows:

$$Loss\ of\ Resilience = \int_{t_{event}}^{t_{recoverd}} F_{initial} - F(t) \tag{1}$$

For the analysis on the network level, the road transportation system can be converted into an abstract graph representation. A graph as a mathematical object is an ordered pair comprising of a set of vertices (or nodes) and a set of edges (or links). In the present case, the road network is modelled by representing intersections as vertices and road segments connecting these intersections as edges. The network analysis relies on centrality measures from the mathematical field of graph theory. These measures are well known in the analysis of social networks, but have also been applied to identify important nodes in transportation networks (Kermanshah et al., 2014; Derrible, 2012). The present approach is focused on betweenness centrality which measures how often a vertex lies along the shortest path between two other vertices in a graph. The original road network data and the corresponding abstract graph are represented in Geographical Information System (GIS). The network preparation as well as the network analysis is realised within GIS. The present approach examines how centrality measures change as certain links fail due to a disruption. For instance betweenness centrality can serve as a proxy for flow indicating how traffic is redistributed in the network.

A real world example of a closure of a highway bridge is used to validate the model comparing the time periods before the disruption and after the disruption with respect to recorded traffic data and the calculations of the model based on centrality measures. Concerning the calculations on network level, Harder et al. (2018) have shown that the predicted change by the model is in line with the observed actual change of the amount of traffic. In order to enhance the model, additional information from the underlying road network such as the type of the road will be included to get even more accurate results.

In addition, it was examined which organisational and technical conditions must be created for the responsible authorities to react immediately in case of an extreme event. A methodology was developed for selecting and prioritising resilience measures in the corresponding resilience phase "respond". Beyond that resilience measures were identified which contribute to an improvement of the robustness of the system and reduce thus the loss of the system functionality in the case of a disruption. Resilience measures in the context of the resilience phase "recover" contribute to a faster recommissioning of elements of the road infrastructure after a disruptive event. The final result is the development of a holistic resilience approach that quantifies and predicts the availability and security of road infrastructure in extreme events in order to identify future hot spots in the road network with the need for further action.

4.2. The availability and safety of impounded waterways regarding heavy rainfall events

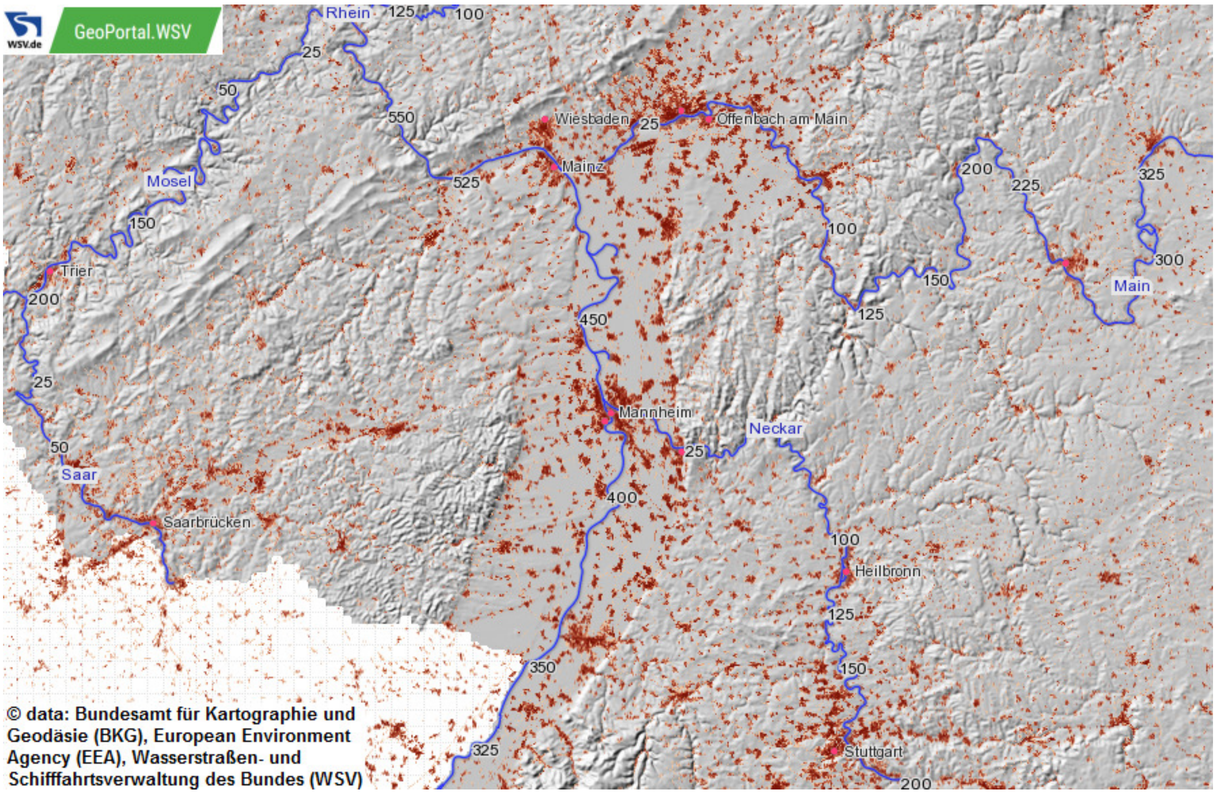
The German Federal Waterways Engineering and Research Institute (BAW) provides expert opinions, consultancy and research relating to waterways engineering tasks. One of the topics that the BAW addresses is discharge and water level control at impounded waterways. The main purpose of discharge and water level control is to keep the water level within a prescribed tolerance range and to decrease discharge and water level fluctuations, which ensures safety and availability as well as ease of navigation.

Discharge and water level control can be disturbed by unexpected lateral inflow. This is the case, for example, for the pilot project at the Hofen impoundment on the river Neckar where unexpected lateral inflow results from combined sewer overflow events from the main sewage collector Nesenbach of the city of Stuttgart. The average discharge of the Neckar River is around 50 m^3/s and the average low water discharge is only 12 m^3/s. Due to heavy rainfall events, up to 130 m^3/s are discharged from the overflow basin of the Nesenbach sewer into the Hofen impoundment. Because of the inflow surge, the water level can exceed and undercut the limits of its tolerance range to a large extent. This affects the safety of navigation as well as the availability of the waterway by causing insufficient clearance height under bridges and insufficient fairway depth.

Within the BMVI Network of Experts, discharge and water level control at impounded waterways is being improved in order to enhance the availability and safety of navigation concerning heavy rainfall events in urban catchment areas. Amann et al. (2016) provided a new control strategy for impounded waterways which is based on a model predictive feedforward control. In close cooperation with the DWD, this model predictive feedforward control is combined with forecasts of lateral inflow from combined sewer overflow using high-resolution and short-term weather forecasts. Kasper et al. (2018) have shown by means of simulations that water level and discharge fluctuations caused by overflow events from the Nesenbach sewer can be significantly reduced in this way.

Due to the collaboration in the BMVI Network of Experts, the approaches and methods used and investigated at the BASt have become known to the BAW. In this way, the concept of vulnerability, mentioned for example by Harder et al. (2018), is now being applied to investigate possible weaknesses of the discharge and water level control. As part of a vulnerability analysis, three aspects are studied. First of all, disturbances of the discharge and water level control depend on the amount of lateral inflow which is determined by the duration and intensity of a heavy rainfall event. Furthermore, characteristic properties of the impounded river reach and the relevant catchment area have to be identified which make discharge and water level control vulnerable to combined or separate sewer overflow events. An example for a characteristic property is the ratio of impervious surfaces in the relevant catchment area or the storage volume of the impounded river reach. The third aspect is the capability to adapt the currently available control and communication technology in order to make use of the model predictive control strategy combined with forecasts of lateral inflow from combined sewer overflow.

The map client GeoViewer.WSV that is provided online by the German Federal Waterways and Shipping Administration (WSV) is used to compare geographical information on the associated catchment area of impounded river reaches in Germany.



© data: Bundesamt für Kartographie und Geodäsie (BKG), European Environment Agency (EEA), Wasserstraßen- und Schifffahrtsverwaltung des Bundes (WSV)

Fig. 1 Map extract from the map client GeoViewer.WSV showing a digital terrain model (grey), the imperviousness density in 2015 (red) and the network of the federal waterways (blue) in the southwest of Germany

The results of the vulnerability analysis will help to identify more impounded river reaches that may be affected by water level and discharge fluctuations due to combined or separate sewer overflow events.

4.3. Probabilistic high-resolution short-term weather forecasts for resilience management

The German Meteorological Service (DWD) constantly improves the quality of its weather forecasts by developing new high resolution models, advancing sophisticated algorithms in data assimilation and incorporates more and better observations. For remote sensing of precipitation DWD operates a radar network over Germany which provides comprehensive measurements on a 1 km x 1 km grid. From these observations predictions are generated every 5 minutes with a maximum lead time of two hours by empirical models (Nowcasting). Within the research topic “Increasing the reliability of transport infrastructures” in the BMVI Network of Experts, the DWD’s activities are twofold: first, introducing new algorithms for setting initial condition perturbations to obtain a reliable ensemble prediction Systems (EPS), and second, providing specific forecasts of heavy precipitation to BAW in order to support their system for automated discharge and water level control at navigable waterways (Kasper et al., 2018).

The probabilistic Numerical Weather Prediction (NWP) system at DWD consists of a global ensemble with 40 members based on the deterministic ICON model (ICON-EPS). The ensemble uses a grid of 40 km horizontal resolution with a refinement over Europe of 20 km. The ICON-EPS provides boundary conditions for convection permitting simulations with the limited area COSMO-D2-EPS at 2.2 km resolution over Germany for lead times up to 27 h every three hours. The spread of the COSMO-D2-EPS simulations heavily underestimates the observed forecast error. Although the forecasts overall match the observations quite well, fine scale structures are often predicted in the wrong places. These forecast errors of the COSMO model not only arise from model deficiencies or wrong initial conditions but might also be due to misplacements in the boundary conditions from the global system, which suffer from diversity and physical consistency of the single member forecasts. To improve these we developed an algorithm (Winkler et al., 2019) which is able to generate flow dependent initial condition perturbations in the ICON-EPS at relatively low computational costs.

To support the BAW project the NWP ensemble forecasts from ICON-EPS, COSMO-D2-EPS and the Nowcast predictions are aggregated for a pilot scheme in a catchment area of the city of Stuttgart at the Neckar River. Predictions are regularly provided during the demonstration phase in 2019 on a pre-operational basis. This includes the single forecast scenarios from the different systems as well as combined forecast products.

Forecasting extreme precipitation events is quite difficult and although a significant number of ensemble members predict a certain amount of precipitation, these events might not be located in the same place nor occur at the same time. Nevertheless, they may belong to a larger scale weather pattern of enhanced predictability. To upscale the forecasts an adaptive neighbourhood method was developed. As an indicator for local predictability the past (lagged) forecasts from the EPS were used. It was assumed that the more consistent the EPS forecasts from the past, the larger is the predictability of the event and the smaller should be the local neighbourhood. This assumption is an attempt to maximise the usability of the forecasted probabilities for a catchment of about 40 km^2 which fits well in a single grid box of the ICON-EPS.

4.4. Assessing resilience of railway infrastructure concerning meteorological and climate hazards by analysing norms and regulations

Climate change is one of the great challenges of our time. Many institutions such as the DWD deal with the forecast of the effects of climate change. Since different prognoses are produced and compared, useful and partially reliable information about the changes can be gathered. That will allow us to anticipate consequences of climate change. For this, the results from the forecasting models have to be compared with the currently used constructions.

Civil engineering is strongly based on the fact that norms and regulations build a framework in which the construction of buildings is safe. The rules have been developed from pure empirical values to scientifically validated rules. In addition models are sources of information for creating and adjusting regulations. The resulting rules are constantly checked, both by reality and by improved models.

One of the projects of the Federal Railway Authority (EBA) is an attempt to better take into account the anticipated increased impacts of climate change. Changed requirements should be implemented in the planning of new infrastructure structures as soon as possible. As a first step, an analysis of the existing regulatory framework has been carried out to identify those rules where climate change is forcing adaptation. Basic assumptions are made to find the passages where the effects of climate change require a change in the regulatory framework. So the first step taken is not yet the attempt to adjust the regulations, but the identification of possibly affected statements. Basic assumption for this evaluation is that the temperatures increase on average, that there are extended stable weather phases and that there are more extreme weather events. The combination of these parameters leads to a fragmented breakdown of the effects, e.g. the increased release of dust on dry surfaces or the possible heat dissipation. Therefore, intermediate categories were formed in which the corresponding effects were subsumed.

As possible changing variables were added:

- temperature (heat and frost)
- precipitation (rain and drought)
- keraunic level, and
- storm.

As a result, central regulations for railway operations were examined in which 1650 statements with a need for adaptation were identified. Of these passages, 201 are classified as targeting usability and 120 may have an effect on sustainability. The analysis, together with the results of the climate modelling, forms the basis for the revision of the regulations. The aim is to normatively record the effects of climate change and to be able to create structures that are suitable for the changed requirements as soon as possible.

Conlusions

This paper highlights the benefits of the cooperation between the departmental research facilities and executive agencies BASt, BAW, DWD and EBA in the BMVI Network of Experts. Different methods are being developed to assess and enhance transport resilience to disruptive events. During their work, the participants exchange their expertise and experience in the fields of weather and climate forecasting, vulnerability and resilience studies as well as norms and regulations in civil engineering.

The methods developed in this co-project will be tested by carrying out pilot studies for each mode of transport. To support planners and operators of transport infrastructure, the results will be provided in the form of practical recommendations and technical guidelines. In this way appropriate actions can be taken to prepare infrastructure systems in order to handle the needs of the future and to be prepared for unknown events that may occur.

Acknowledgements

This work is carried out within the framework of the BMVI Network of Experts "Knowledge – Ability – Action" (https://www.bmvi-expertennetzwerk.de) funded by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) as part of the research project entitled: "Quantification and prognosis of the availability and safety of road infrastructure during extreme events", which is a component of the topic "Increasing the reliability of transport infrastructures".

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