Berg Heinz-Peter
Formerly Bundesamt für Entsorgungssicherheit, Salzgitter, Germany

Petrek Nicolas
IVBB mbH, Braunschweig, Germany

Threats and possible approaches of vulnerability assessment of natural hazards on road infrastructure

Keywords

natural hazards, risk assessment, hazard management, road infrastructure, autonomous driving

Abstract

Natural hazards are frequently causing disturbances for different types of infrastructures, in particular for transport systems. Flooding and storm are considered as major threats to these systems. Based on examples of natural hazards' impact on roads, possible approaches of vulnerability assessment are described. In order to reduce the threats resulting from natural hazards on road transport, appropriate technical countermeasures to increase resilience and robustness for continuous road safety and mobility are necessary. Moreover, the behaviour of the driver is also an important factor to avoid accidents in case of specific weather conditions. Autonomous driving may support a reduction of accidents in the future and, in particular, necessary evacuation processes in cases of wildfires or hurricanes.

1. Introduction

Over the past three decades, most natural disasters (90%) have been caused by climate related events and extreme climatic events are likely to become more frequent because of global warming. In its Summary for Policymakers [30] based on the Fifth Assessment Report published in 2014 the Intergovernmental Panel on Climate Change (IPCC) states that among other extreme weather and climate events the frequency or intensity of heavy precipitation events has likely increased in North America and Europe.

One recent example in Germany was the hurricane "Friederike" with recorded wind speeds of more than 200 kilometres per hour which hit the west and the centre of Germany on 18th January 2018 and caused severe damages. According to the German Weather Service, "Friederike" is the heaviest hurricane since the storm "Kyrill" in 2007.

Such weather phenomena have a substantial impact on safe operation of critical infrastructures like power systems, on modes of power generation and power consumption. Influence of weather conditions on the electrical power industry is diversified. Typical examples are power lines, but also the telecommunication infrastructure is quite vulnerable and possesses fragile objects in case of extreme weather situations due to their high interconnection [24].

In case of "Friederike", for more than 120 000 people in North Rhine-Westphalia and the neighbouring German Federal States disruptions and power outages occurred. The main reason were trees that had fallen on overhead lines.

The hurricane "Friederike" is also an example for weather impact on the different types of transport infrastructures. The railway stopped the long-distance traffic nationwide for security reasons. Flight operations were also affected by "Friederike". Several airports have to cease operations. In Hanover, the dispatching of starting engines was stopped. Because pilots had difficulty landing their aircraft which swirled dangerously through the air, sometimes it took several attempts to land. Therefore, the Hanover Airport was closed for a certain time.

As well as in case of railways [4], extreme weather events can also have a significant negative impact on the road network. In recent years, the occurrence of extreme weather events across Europe, such as rain induced landslides, river floods, winter storms and hurricanes, increases.

These hazards result in disruption or disablement of the traffic networks and sometimes in very serious car accidents. Influence of weather related variables such as rain, snow, fog, extreme temperature and other weather-related disasters on road accidents are well established globally (e.g. [1], [32]).
The different weather related phenomena affects road conditions like changes in visibility, pavement friction, lane obstruction, lane submersion, etc., which eventually increase the risk of accident [5].
These natural hazards occur not only in North America and Europe, but worldwide as described in several publications, for instance in [29] for Malaysia, [12] and [15] for China and [19] for Australia.
Examples of the impact from those weather related phenomena on road infrastructure in Europe and, in particular, recent accidents in Germany will be provided in section 2 as well as approaches for the identification of general weather impacts. On this basis section 3 will show the hazard assessment and possible countermeasures for reducing the negative effects on infrastructures and the integrity of the transportation system in Europe.

2. Examples of the impact of natural hazards on roads

In the past years, extreme weather events have led to some incidents in the European transport systems. The existing vulnerability to extreme weather of transportation infrastructure has led to several efforts in order to fundamentally reduce those negative effects. Therefore, the understanding of the weather effects threatening the integrity of existing infrastructure is a key element to identify effective countermeasures.
One approach to identify relevant weather hazards was elaborated within the European research project RAIN (Risk analysis of Infrastructure Networks in response to extreme weather) [24] resulting in a list of 14 severe weather hazards which includes:

- heavy rainfall,
- windstorms,
- coastal floods,
- river floods,
- landslides,
- lightning,
- tornadoes,
- hail,
- convective windstorms,
- snowfall and snow storms,
- icing,
- snow loading,
- wild fires, in particular forest fires and
- freezing rain.

In the following, we will illustrate some of these severe weather hazards.
In April 2011, a massive pile-up has taken place on the Autobahn A19 near Rostock in the German Federal State of Mecklenburg-Western Pomerania involving up to 80 cars on both lanes leading to 10 fatalities and 97 injuries shown in *Figure 1*.

Figure 1. Accident after a rapidly sandstorm on a highway in the northern part of Germany in April 2011.

The causes of the accident were suddenly occurring strong winds which whirled up sand from adjacent dry fields. This sandstorm resulted in a situation with visibility below 50 meters on the four-lane highway hitting most of the drivers without any warning. In the ongoing, 17 cars and three trucks including a tanker which carried dangerous goods caught fire and several people were trapped in their car.
In the introduction, the hurricane “Friederike” and its serious impacts in Germany were already shortly discussed. In this context, on the motorway A44 in the district of Kassel the trailer of a truck overturned because of a gust of “Friederike” shown in *Figure 2*. After the accident, the road was temporarily closed. Subsequently, only one lane of the A44 was passable. In the opposite direction a trailer threatened to fall off the bridge. "Miraculously, another gust hit the trailer and raised it again," a police spokesman said.
Such extreme weather events involve not only suddenly occurring strong winds but also heavy precipitation. Land-based transportation infrastructures like roads and railway lines are particularly affected by those events of heavy precipitation [13].
Against this background, [23] found a general increase in extreme participation events for daily, multi-day as also for sub-daily events. In addition, the findings suggest that central Europe will start to see previously unusual heavy precipitation events also during the winter period.

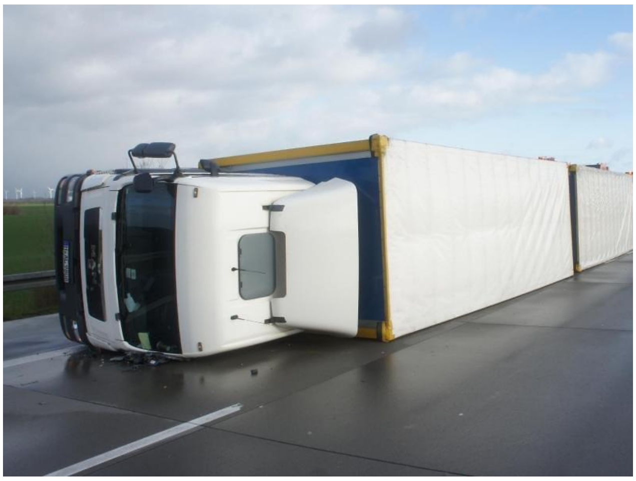


Figure 2. Accident of a truck and its trailer which were overturned by strong gusts of "Friederike" in January 2018

In end of July 2017, a period of continuing heavy precipitation of the low pressure area "Alfred" lead to major flooding in the Federal States of Lower Saxony, Saxony-Anhalt and also in Thuringia around the low mountains area of the Harz. In some parts of central Germany, the average rainfall of one month occurred within two days resulting in closed roads in the whole region (*Figure 3*) including flooding of the inner city of Goslar.

Figure 3. Closed road due to flooding near Braunschweig/ Germany in July 2017.

In the alpine region of central Europe heavy precipitation events cause slope slides, collapsing road and track structures as well as debris flow [35]. Although [8] is expecting a general decrease of winter-related costs due to expected milder winters and, therefore, also less snow due to higher temperatures, heavy precipitation events in this area during winter time can lead to heavy snowfalls with major effects on the transportation infrastructures.

In January 2018, the German Weather Service recorded quantities of new snow between 2.5 and 5 metres in the period between 30.12.2017 and 23.01.2018 for the region around Davos Switzerland which are a 75-year event.
Also in the region around Zermatt heavy snowfalls shown in *Figure 4* were responsible for closed roads and railway tracks as well as the highest avalanche danger which resulted in 13.000 tourists not able to leave Zermatt for two days.

Figure 4. Closed track section near Zermatt due to heavy snowfalls in January 2018.

Generally, landslides in sensitive clays represent a major hazard in the northern countries of the world such as Canada, Finland, Norway, Russia, Sweden and in the US state of Alaska. Past and recent examples of catastrophic landslides at e.g. Saint-Jean-Vianney in 1971, Rissa in 1979, Finneidfjord in 1996 and Kattmarka in 2009 have illustrated the great mobility of the remolded sensitive clays and their hazardous retrogressive potential [21]. The different impacts of landslide-induced road network interruptions on communities in a rural area in the European Alps are examined in [27].
A significant part of the transport infrastructures in Eastern and Central Norway is placed on sensitive clays, and a large number of new r roads in these regions are being planned on sensitive clay deposits [31]. Thus, Norway is considered an important region for landslide investigation as it is particularly prone to landslide hazards due to topography, geology and weather [17].
The cause of a slide and the triggering of a slide may not be the same thing. The cause of the so-called Soerkjosen slide in 2015 has been identified to be the presence of a deep clay layer and the loading by filling crushed rock into the sea for a road crossing. The actual slide was finally triggered by heavy rain and snow melt half a year later [25].
Therefore, as a further example a recent landslide on a road in Norway is provided. From the slope of the mountain a huge landslide came down on the highway

E16 on the 9th of June 2016 as shown in *Figure 5*. The highway connecting Oslo and Bergen was blocked for some days. A truck was thrown at least 22 meters and landed on its side; the driver escaped death by a "matter of millimetres".

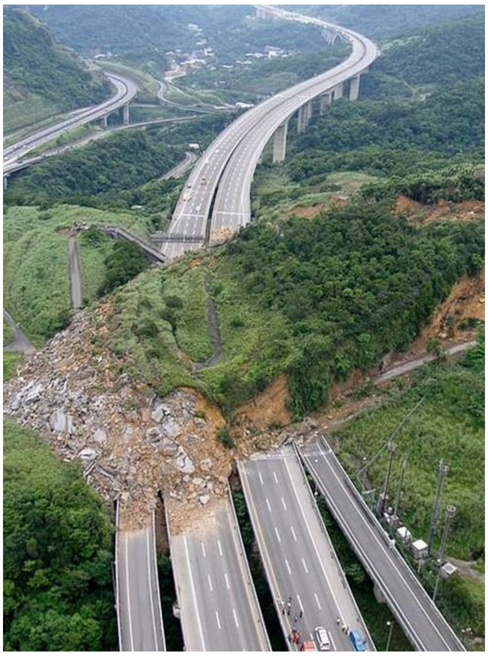


Figure 5. Closed highway due to landslide in Norway in June 2016.

Since 2013, a landslide early warning system has been operational at the Norwegian Water Resources and Energy Directorate and a specific method entitled "event, duration matrix, performance" (EDuMaP) has been chosen to test the performance of this early warning system for weather-induced landslides [26].
These five examples of the past few years illustrate some of the possible consequences of extreme weather events on the transportation infrastructures and in particular on roads.
Beside the RAIN project already mentioned before at the beginning of this section a similar approach to identify general weather impacts on infrastructure of the transport systems was conducted by the EWENT project (Extreme Weather impacts on European Networks of Transport). Key element of this report is the questioning what is extreme, where and to whom [34]. *Table 1* shows exemplarily the findings for hail and the references as well as the country of study. As a result, *Table 1* creates a connection between the size of the hail and the possible impacts on the transport system.

	Hail			
Size (cm)	Impacts on transport system	Reference	Country of study	Validity area / region
≥ 1.5/ long duration	• Slippery roads and poor visibility.	Rauhala et al. 2009	Finland	Everywhere
2–3	• Occasional damage to car sheet metal.	Rauhala et al. 2009	Finland	Everywhere
3–5	• Damage to car sheet metal and windshields cracked.	Rauhala et al. 2009	Finland	Everywhere
≥ 7	• Car windshields completely broken, large dents in sheet metal.	Rauhala et al. 2009	Finland	Everywhere
≥ 7	• Damage to 70 000 vehicles and 23 aircraft.	Schuster and Blong 2004	Sydney, Australia	Australia

Table 1. Impact of hail on transport systems which depend on the size of the hail according to [34].

In the ongoing, these data can be used to assess the vulnerability of a certain part of the transport infrastructure regarding the impact of natural hazards in order to take appropriate measures. The different approaches will be introduced and discussed in the following section.

3. Approaches of hazard assessment

A general approach in the area of hazard assessment was made by [11] for the interdisciplinary research project "Impacts of extreme weather events on infrastructure in Norway (INFRARISK)". The main goal was the identification of the relationship between climate change and the frequency, intensity and distribution of extreme weather events as well as the assessment of the vulnerability of the infrastructure regarding those events.
In a first step those weather events with the most serious impacts on transport infrastructure similar to the approach of [34] have been identified in [11].
In the next step the INFRARISK project assessed the influence of different climate variables on this particular event. Furthermore, the project addresses the questioning how the frequency, intensity and distribution of such events will change in the future against the background of the progressing climate change. For the most frequent natural hazards snow avalanches, debris slides/flows, rock fall and flooding, historical data and the possible development in the future have been analysed.
The historical datasets for the area of Norway exists from the present back to the year 1957. These datasets contain the daily temperature and the precipitation measurement and can be interpolated on a grid of 1 x 1 km. On the basis of the temperature and the precipitation the parameters for snow can be derived by the use of hydrological models.
Observational data for wind go back until the year 1961 and show an increase in the annual wind strength of approximately 7-8 % to date for major parts of Norway.
On the other hand, the future trends were derived from seven existing scenarios taken from general circulation models, which were downscaled to regional climate models and statistically adjusted

under inclusion of topographic information and observations of a grid of 1 x 1 km. This provides the basis for the assessment of the exposure of the transport infrastructure to extreme weather events.

In order to assess the exposure for snow avalanches and rockslides the national road and railroad network of Norway was combined with susceptibility maps for this two hazard types. In contrast, the hazard type of debris flow was assessed on the basis of empirical data which was used to determine critical conditions for the initiation of debris flows.

Therefore, the statistical correlation between intensity and duration of rainfall and the distribution of debris flows was examined by using intensity-duration threshold curves resulting in thresholds defining critical intensities over durations up to 7 days.

Furthermore, a risk model was developed which estimates risks for each hazard type and calculates a risk value for each infrastructure element at risk resulting in hazard zones for transport routes from interest and delivering expected closure rates and related costs for each element as well as expected event frequency for each element at risk shown in *Figure 6*.

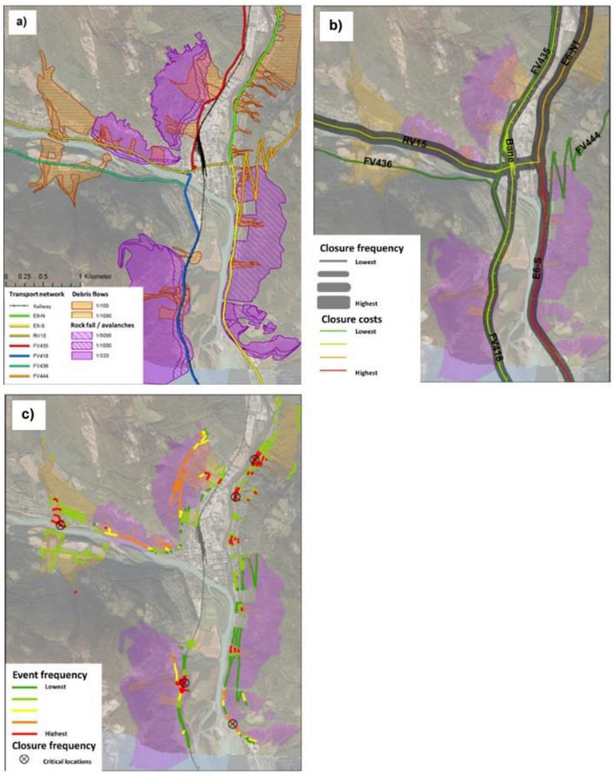


Figure 6. Hazard zones (a), expected closure rates and related costs (b) and expected event frequency (c) for an exemplarily infrastructure element according to [11].

Despite uncertainties in the climate scenarios and inaccuracy due to the downscaling in complex topography the findings of the INFRARISK project deliver strong indications that impacts of extreme weather events on infrastructure will likely increase in the future. This is true for precipitation induced events due to an expected further increase in the annual precipitation as well as a likely increase in frequency and intensity of moderate to strong short-term precipitation events. Moreover, the observed effect of increased wind speed over the last decades will likely persist.

Against this background [11] states that mitigation against natural hazards is expensive and in most cases only be established after an incident has occurred.

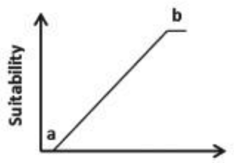
This consideration is directly linked to the approach described in [16] discussing the spatial multi-criteria analysis of natural hazard susceptibility in the field of early road planning in order to avoid areas with high vulnerability to natural hazards. Therefore, seven criteria were used for the three weather indicated events flooding, land sliding and debris flow:

- topographic wetness index (TWI),
- land cover (urban, agriculture, forest etc.),
- geology of the certain area,
- soil thickness,
- slope angle respectively the rate of maximum change in elevation,
- distance to streams, and
- distances to lakes.

The multi-criteria analysis provides a procedure for analysing complex decision problems e.g. in road planning by dividing the complex problem into small parts which are the criteria. If Geographic Information Systems (GIS) are combined with multi-criteria analysis, decision makers get information regarding consequences, uncertainties and their spatial distribution. This approach is entitled spatial multi-criteria analysis (SMCA).

SMCA uses fuzzy membership functions and threshold values to determine the value of each criteria regarding each perspectives for the considered area. For example, in case of the criteria distance to streams, a linear monotonically increasing fuzzy membership function is used with threshold values for the three perspectives as shown in *Figure 7*.

Regarding land sliding the function and the threshold values show that the suitability of a certain landmark respectively cell has the lowest value for zero meter distance to streams and reaches a constant high value with a distance to streams of 300 meters and above.



	Threshold values	
Flooding	a=0m	b=200m
Land sliding	a=0m	b=300m
Debris Flow	a=0m	b=200m

Figure 7. Fuzzy membership function and threshold values for the criteria distance to streams in SMCA application according to [16].

This has to be done for each cell in order to assess the suitability regarding each of the seven criteria. In a next step, the SMCA uses weighting to indicate the judgement of importance of the factors which defines how the criteria are aggregated to an overall assessment. This can be done by a multi-attribute weighting method with or without expert judgement or a weighted linear combination (WLC) with either equal weights or a factor indicated method which considered the effect of each factor on all other factors.

It is shown in [16] that all three methods for weighting are applicable whereas WLC is one of the most common decision rules. Moreover, SMCA is a useful method to realise a susceptibility assessment and spatially identifying areas which have the potential for natural hazard indicated events [16]. Furthermore, multi-criteria analysis and in particular SMCA has been already used for landslide hazard assessment for instance in [9] or for urban flood hazard zooning [10].

In contrast, in [33] a dynamic risk simulation for the assessment of natural hazards along roads in Switzerland is discussed and compared with the static approach. The dynamic approach considers traffic variations and interactions between vehicles such as slowdowns or tailbacks in front of traffic lights. Hence, the main innovation in the dynamic approach is the consideration of the duration which vehicles are located inside a hazardous area. Therefore, a microscopic dynamic traffic simulation was developed within MATLAB for the ability to analyse and recognise each vehicle and its time within the designated area.

The modified equation to calculate risks on roads is provided in (1):

$$R_{ob} = F_e * P_s * N_V * \lambda * \beta \qquad (1)$$

where R_{ob} is the object risk [fatalities yr^{-1}], F_e is the occurrence frequency of an event [yr^{-1}], P_s is the proportion of the hazardous section affected by the event [-], λ is the death probability in case of an vehicle affected by the hazard [-], β is the average vehicle occupation [person/vehicle], and N_v represents the number of equivalent vehicles exposed to the hazard within the hazardous section derived from the average number of vehicles per day, the average vehicle speed and the length of the section.

In contrast, the dynamic object risk approach expressed in equation (2) does not consider the number of equivalent vehicles exposed to the hazard on the basis of the average number of vehicles and their average speed but rather by counting the actual number of simulated vehicles and their duration time within the section:

$$R_{ob} = F_e * P_s * \frac{t_{cum}}{t_{sim}} * \lambda * \beta \qquad (2)$$

In this context t_{cum}/t_{sim} expresses the relation of the cumulated time of vehicles which are located in the hazardous area to the simulation time. Thus, a t_{cum} value of 180 seconds during a simulation time of 60 seconds is an equivalent of 3 vehicles constantly located within the section or 18 cars which enter the section and leave it after 10 seconds within the simulation time.

On basis of this new approach it can be shown that dynamic risk simulation delivers a more realistic risk assessment in case of mountain roads. Signalization leading to tailbacks within hazardous section in front of a tunnel entry, for instance, or road closures due to rock fall or landslide can significantly increase the number of equivalent vehicles exposed to the hazard within the dynamic approach resulting in risks up to 2.5 higher under specific conditions [33].

Recently, there are further efforts for the estimation of risks related to road networks which have an increasing detail level. [14] has established a methodology for the risk assessment of the potential impact of flood and mudflow events to road network in Switzerland. In the methodology, a specific area of study is exposed to rainfall events which resulted in hazardous events like flooding and mudflow.

Moreover, the model is able to assess direct costs to the network caused by the event like clean-up, repair or reconstruction activities as also indirect costs like loss of connectivity and extended travel time by linking the direct consequences of the event with the dynamics of the road network.

Nevertheless, the use of various models for precipitation and in the ongoing for flooding, landslides and, in addition, for traffic requires a fundamental understanding for the correlation between the models and the appropriate application. Although models like these become more and more complex, it has been shown that they can be adapted and applied to other natural hazards [18].

4. Concluding remarks

Hazards are the climate-induced forcing, such as heat waves and storms, which will lead to physical and operational impacts on infrastructures all over the world. Their configuration, strength and frequency depend on climatic averages which have to be investigated based on a sufficient set of data for the respective local area. For example, hotspots of droughts, floods, landslides and storms were identified in central, southern, southwest and southeast areas of China.

Therefore, questions requiring answers are: how does the road network cope with extreme natural hazards and how can the its resilience be improved?

The examples provided in section 2 are typical severe weather hazards identified in the RAIN project. Their consequences have to be assessed according to the specific local conditions. For those assessments appropriate methods have to be applied as described in section 3.

For example, Australia's variable climate has always been a factor in natural disasters that have had significant impact on an evolving road infrastructure and on the communities that rely on the roads. Increasing frequency and intensity of natural hazards in Australia has led to scenarios where the infrastructure is subjected to loading regimes beyond those prescribed in the current design codes. Just recently, on January 7, 2018, wild fires in Australia resulted in a heatwave with temperatures strong enough to melt the bitumen on a 10 km stretch of a highway in Victoria and underlined the need also for this type of natural hazard.

Therefore, a project entitled "Enhancing resilience of critical road infrastructure: bridges, culverts and flood-ways under natural hazards" has been planned with the following steps [28]:

- developing and validating a method for vulnerability modelling of critical road structures, e.g. under flood and bush fire,
- simplifying the analysis methods for network wide application,
- developing a ranking of road structures for the state of Victoria/Qld for the selected hazards,
- elaborating a design guideline for resilient floodways.

This project has been started in January 2014 for a 6.5 year period and, thus, will be finalized in June 2020. Results of this project could be worthwhile not only for Australia.

Infrastructure maintenance plays a key role in resilience and sustainability build-up. Favouring reliable sub-systems is making the transport system more resilient. Resilience can be divided into components and sub-components as any semantic concept. The aim for disaggregating the concept is to make resilience manageable, measurable and understandable and applicable to transport systems [20].

The deterioration models applied by the infrastructure managers are typically probabilistic (e.g. Markovian chains) or deterministic (e.g. deterioration curves). Also very heuristic practices are in place [19]. What is in most cases missing is the system dynamics between the structural components. Yet it is known that for example maintaining pavements, cleaning drainage and removing snow stacks can have a substantial impact on the life-cycle of the infrastructure.

Another aspect is the role of the drivers and careful thought will need to be given to the issue of driving in degraded conditions – including those arising from severe weather. As far as road safety is concerned, the driver is the centre point. He has to be made aware that his attitude of driving strongly influences his own safety but also the safety of the other participants on the road [3]. Everything depends on how he handles the vehicle. Therefore, it is important that the driver does not break existing rules. For example, since December 2010, supplemented in 2017, there is an obligation in Germany according to the national road traffic regulations to use winter tires. Nevertheless, as checks by the police have shown even on roads in some mountain areas this rule has been broken by the drivers and the cars blocked the respective roads.

Another requirement is that the driver has to intervene when the autopilot of his car asks him to do so, for instance because the technology recognizes in bad weather conditions or a confusing traffic situation that it no longer has a clear view. However, the driver must also take over again if he "recognizes" himself or has to recognize due to obvious circumstances that the prerequisites for a proper use of the automatic driving function no longer exist.

On the other hand in the event of a nature-induced disruption to traffic flow in major travel corridors or networks, the connected vehicles capability of automation in driving can identify alternate routes with available capacity to accommodate traffic overloads, and smart route diversion will come into effect as a dynamic resilience measure. However, this will be a task not solved in the near future.

But maybe there are other advantages by using autonomous cars.

During one of the seven "Wine Country" fires in Northern California in autumn 2017, one family become very lately aware of the critical situation because of the failure of existing public safety systems to warn of impending disaster and ensure that residents evacuate safely. Once on the road to emerge from the wild fire, the family chose their usual way out of the area, only to be stopped by a wall of flames. Luckily, a fire crew was there to direct them to a less travelled, and less familiar route.

Could autonomous vehicles save lives in disasters? Autonomous vehicles may provide life-saving assistance in the event of a large-scale evacuation, if a shared fleet of autonomous vehicles is built with this purpose in mind. Dispatch systems could have calculated and optimized timing and order of the evacuation based on risk and optimal evacuation route capacity.

One further important task is a modification of technical standards and criteria to better match estimates of future climatic conditions. The re-evaluation and modification of planning and technical criteria will potentially influence the scope and placement of future projects as well as adjustments in construction techniques and materials employed to better reflect the demands of a potentially more variable and extreme climatic conditions. More research, however, is necessary to better understand how these criteria and standards are currently established and enforced in order to identify the relevant actors and institutions.

The increasing global temperatures and sea levels, as well as changes in weather patterns have significant impacts on transportation infrastructure systems. Sea-level rise is recognized as a major threat to transportation systems, especially in coastal areas, by increasing the number of flooding events, storm surges, and beach erosion. The increase in precipitation as well as the frequency and magnitude of inland flooding expedites the erosion of roads and bridges and makes them more vulnerable to failures. The impacts of sea-level rise on road infrastructure are mainly [7]:

- erosion and subsidence of road bases,
- flooding of underground tunnels and low-lying infrastructures,
- flooding of road lines,
- traffic congestion, and
- infrastructure damage due to increased storm intensity.

The climate change simulations also suggest that the areas affected by heavy precipitation events may become larger in many European regions especially for sub-daily events. This can have consequences for infrastructure networks. Larger scale events may damage more infrastructure elements at the same time [13].

The exposure of the Norwegian transport infrastructure to selected hazard types, such as snow avalanches, rock fall and rock slides, was estimated through GIS-analyses. Uncertainties in the analyses are mainly linked to the uncertainties in the various climate scenarios, the scarcity of observations (weather stations) and the downscaling in a complex topography.

Moreover, the analyses also show that the frequency and intensity of moderate to strong short-term precipitation events are likely to increase quite significantly. These are all trends that will lead to increased number of precipitation induced natural hazard events. Robust wind data are sparse and therefore analyses are uncertain. The trends indicate however, an increase in wind speed over Norway. Strong winds pose a problem to roads in itself, in addition to being the key factor in snow drift [11].

US researchers have used satellite data to calculate that sea level is rising twice as fast as previously thought [22]. Respective expectations are inferred from tide gauge data [6].

This prognosis would mean that the sea level of the German coast at the end of the century would be already 65 cm higher and not, as previously expected, only 30 cm. This also requires adequate planning of the road infrastructure in the Northern part of Germany.

International cooperation between national road owners can aid structuring and implementing climate change adaptation strategies throughout the European network. Climate change adaptation on roads can be defined as the concrete measures implemented to reduce vulnerability to more extreme weather phenomena in the future in order to increase resilience and robustness for continuous road safety and mobility.

Climate change adaptation is gaining more general interest and political focus since actions of mitigation to climate change no longer seem to easily provide sufficient effect to future sustainable transportation on roads [2].

Therefore, on European level a specific group of CEDR on mitigation and adapting to climate change has decided to initiate, develop, and/or complete climate change adaptation measures: strategy and action plan, awareness, risk methodology approach. CEDR is the road directors' platform for cooperation and promotion of improvements to the road system and its infrastructure, as an integral part of a sustainable transport system in Europe, i.e. a platform for cooperation between National Road Authorities.

References

[1] Amin, M.S.R., Zareie, A. & Amador-Jiménez, L.E. (2014). Climate change modeling and the weather-related road accidents in Canada. *Transportation Research Part D: Transport and Environment* 32, 171-183.

[2] Axelsen, Ch., Grauert, M., Liljegren, E., Bowe, M. & Sladek, B. (2016). Implementing climate change adaptation for European road administrations. *6th Transport Research Arena April 18-21, 2016*.

[3] Berg, H.P. (2012). Safety culture from the perspective of road safety, *Proceedings of the International Road Safety Seminar, GAMBIT 2012,* Gdansk, 26 – 27 April 2012.

[4] Berg, H.P. (2017). Risks and consequences of weather hazards on railway infrastructure. *Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars*, Volume 8, Number 1, 1-11.

[5] Bergel-Hayat, R., Debbarh, M., Antoniou, C. & Yannis, G. (2013). Explaining the road accident risk: Weather effects. *Accident Analysis and Prevention*. 60, 456-465.

[6] Dangendorf, S. et al. (2017). Reassessment of 20th century acceleration global mean sea level rise. *Proc. Natl. Acad. Sci. USA* 114, 5946-5951.

[7] De Almeida, B.A. & Mostafavi, A. (2016). Resilience of infrastructure systems to sea-level rise in coastal areas: impacts, adaption measures and implementation challenges. *Sustainability* 8, 1115.

[8] Doll, C., Trinks, C., Sedlacek, N., Pelican, V., Comes, T. & Schultmann, F. (2014). Adapting rail and road networks to weather extremes: case studies for southern Germany and Austria. *Natural hazards* 72, 1, 63-85.

[9] Feizizadeh B., Blaschke T. (2013). GIS-multicriteria decision analysis for landslide susceptibility mapping: comparing three methods for the Urmia lake basin, Iran. *Natural Hazards* 65, 2105–2128.

[10] Fernández D.S., Lutz M.A. (2010). Urban flood hazard zoning in Tucumán Province, Argentina, using GIS and multicriteria decision analysis. *Eng Geol* 111, 90–98.

[11] Frauenfelder, R. et al. (2017). Impacts of extreme weather events on transport infrastructure in Norway. *Nat. Hazards Earth Syst. Sci*. Manuscript under review. Discussion started on: 20 December 2017, https://doi.org/10.5194/nhess-2017-437.

[12] Gao, J. et al. (2016). The association between meteorological factors and road traffic injuries: a case analysis from Shantou city, China. *Scientific Reports* 6, article number 37300.

[13] Groenemeijer, P. et al. (2015). *Past Cases of Extreme Weather Impact on Critical Infrastructure in Europe. Project Report.* Available at: http://rain-project.eu/wp-content/uploads/ 2015/11/D2.2-Past-Cases-final.compressed.pdf (last access: 11 July 2017).

[14] Hackl, J., Lam, J. C., Heitzler, M., Adey, B.T., Hurni, L. (2018). Estimating the risk related to networks: a methodology and an application on a road network. *Manuscript under review. Journal Nat. Hazards Earth Syst. Sci.*

[15] Han, W., Liang, C., Jiang, B., Ma, W. & Zhang, Y. (2016). Major natural disasters in China, 1985–2014: occurrence and damages. *Int. J. Environ. Res. Public Health* 13, 1118.

[16] Karlsson, C.S.J., Kalantari, Z., Mörtberg, U. et al. (2017). Natural Hazard Susceptibility Assessment for Road Planning Using Spatial Multi-Criteria Analysis. *Environmental Management*, 60, 823. *https://doi.org/10.1007/s00267-017-0912-6.*

[17] Kråbøl, E.H. (2016). *Investigating and predicting landslides using a rainfall-runoff model in Southern Norway*. Thesis. University of Oslo, May 2016.

[18] Lam, J. C. & Adey, B. T. (2016). Functional loss assessment and restoration analysis to quantify indirect consequences of hazards. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering* 2. Issue 4.

[19] Leviäkangas, P. et al. (2014). *Extreme Weather Impacts on Transport Systems. Technical Report,* VTT Technical Research Centre of Finland.

[20] Leviäkangas, P. & Michaelides, S. (2014). Transport system management under extreme weather risks: views to project appraisal, asset value protection and risk-aware system management. *Natural Hazards* 72, 1, 263–286.

[21] L'Heureux, J.-S., Locat, A., Leroueil, S., Demers, D. & Locat, J. (2013). *Landslides in Sensitive Clays: From Geosciences to Risk Management*. Springer Science & Business Media.

[22] Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D. & Mitchum, G.T. (2017). Climate-change-driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academic of Sciences of the United States of America*, published ahead of print February 12, 2018.

[23] Nissen, K. & Ulbrich, U. (2017). Increasing frequencies and changing characteristics of heavy precipitation events threatening infrastructure in Europe under climate change. *Nat. Hazards Earth Syst. Sci.*, 17, 1177–1190. *https://doi.org/10.5194/nhess-17- 1177-2017*.

[24] Nogal, M., O'Connor, A., Caulfield, B. & Brazil, W. (2016). A multidisciplinary approach for risk analysis of infrastructure networks in response to extreme weather. *6th Transport Research Arena April 18-21, 2016*.

[25] Nordal,S. et al. (2017. Lessons learned from the 2015 Soerkjosen shoreline landslide in Norway. *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering*, Seoul 2017, 2183- 2186.

[26] Piciullo, L., Dahl, M.-P., Devoli, G., Colleuille; H. & Calvello, M. (2017). Adapting the EDuMaP method to test the performance of the Norwegian early warning system for weather-induced landslides. *Nat. Hazards Earth Syst. Sci*. 17, 817-831.

[27] Schlögl, M., Avian, M., Richter, G. , Thaler, T., Heiss, G. , Fuchs, S. & Lenz, G. (2018). On the nexus between landslide susceptibility and transport infrastructure – agent-based vulnerability assessment of rural road networks in the Eastern European Alps. *Nat. Hazards Earth Syst. Sci. Discuss*., https://doi.org/10.5194/nhess-2018-93, Manuscript under review for journal Nat. Hazards Earth Syst. Sci., Discussion started: 4 April 2018.

[28] Setunge, S. (2017). *Enhancing resilience of critical road infrastructure: bridges, culverts and flood-ways under natural hazards. Annual project report 2016-2017*. Bushfire and Natural Hazards CRC, September 2017.

[29] Shahid, S. & Minhans, A. (2016). Climate change and road safety: a review to assess impacts in Malaysia. *Jurnal Teknologi (Sciences & Engineering)* 78, 4, 1–8.

[30] Stocker, T.F. et al. (editors.). (2013). Summary for Policymakers. Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[31] Thakur, V. (2016). Landslide hazards in sensitive clays: Recent advances in assessment and mitigation strategies. NGM 2016, *Proceedings of the 17th Nordic Geotechnical Meeting, Challenges in Nordic Geotechnic*, Reykjavik, 25th – 28th of May 2016.

[32] Vécsei, P. & Kovács, K. (2014). Statistical analysis of relationships between road accidents involving personal injury and meteorological variables (in Hungary). *Idojaras* 118, 4, 349-378.

[33] Voumard, J., Caspar, O., Derron, M.-H. & Jaboyedoff, M. (2013). Dynamic risk simulation to assess natural hazards risk along roads. *Nat. Hazards Earth Syst. Sci.* 13, 2763–2777.

[34] VTT Technical Research Centre of Finland. (2011). Extreme weather impacts on transport systems, available at: http://www.vtt.fi/publications/index.jsp (last access: 04.02.2018).

[35] Zumbrunnen, T., Thuro, K. & König, S. (2017). Dealing with natural hazards along federal state roads in Bavaria. *Geomechanics and Tunnelling* 10, 1, 34-46.