# Probabilistic multihazard risk assessment for road infrastructure: application to a mountain road in Austria

STEFAN OBERNDORFER [1,2],
PHILIP SANDER[3], SVEN FUCHS[2]

**Organisation(en):**

[1]Chartered Engineering Consultant for Mountain Risk Engineering and Risk Management

[2]Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences

[3]Institute of Construction Management, Bundeswehr University Munich

**office@oberndorferzt.at[1,2], sven.fuchs@boku.ac.at[2], philip.sander@unibw.de[3]**

# Abstract

Natural hazard risk assessment for road infrastructure is usually based on standardized frameworks, which calculates risk in a deterministic manner. However, due to constant singlevalue input data such deterministic standard approaches regularly ignore the epistemic data uncertainty, resulting in potential bias for riskbased decisions on mitigation measures. In our study we supplemented the standard framework by a probabilistic risk analysis (PRA) method to consider these uncertainties in input data. The PRA approach facilitates the quantification of epistemic uncertainty by using probability distributions to represent data uncertainty while a deterministic approach uses single discrete values without uncertainty representation. We compared the results of the PRA with the deterministic risk assessment approach for road infrastructure, based on a case study of a mountain road exposed to a multihazard environment. The results demonstrate that the annual collective monetary risk of the deterministic approach is lower than the PRA outcome due to additional uncertainty consideration. Thus, without consideration of uncertainty of the input variables risk might be underestimated using the operational standard risk assessment approach. Thus, PRA for natural hazard risk generates an important increase in information, which is fundamental for optimal riskbased decisionmaking under budget constraints. This facilitates an increase of knowledge about potential road risk with the effect of a better informed and transparent basis for implementing risk minimization measures for roadsafety authorities, design engineers and policy makers.



## Introduction

So far, the focus in mountain hazard risk analysis is usually on deterministic methods, in particular if road infrastructure is considered. Due to the complex input data needed and the comprehensive but standardized method with a variety of contributing parameters, a considerable degree of uncertainty results. Consequently, contributing variables needed for risk assessment are normally processed as single deterministic (discrete) values rather with probability distributions.

Input data for risk calculation is often defined from expert judgement if no statistical data is available or as mean value based on statistical datasets. Furthermore, standardized frameworks for operational risk assessment considering a multihazard environment, such as Bründl et al., 2009; ASTRA, 2012; Bründl et al., 2015, rely on variables from recommended semiempirical probability classes, e.g. to express hazardspecific vulnerability with indicators or indices (PapathomaKöhle, 2017). Thus, the standard approaches for road risk computation obtain the results with constant input data (discrete single data) usually without considering a potential range to represent data input uncertainty. Therefore, a considerable degree of uncertainty remains which may result in a bias of riskbased decision making. To overcome this gap, we extended the deterministic standard approach with a probabilistic model to include data uncertainty of the input variables. With this probabilistic approach we quantified the epistemic uncertainty by using simple probability distributions of the input data instead of single values without uncertainty representation. The probabilistic calculation of road risk yielded in a probability density function (PDF), which was compared to the deterministic result from the standard guideline for road safety using the framework form ASTRA (2012).

The commonly accepted definition of risk is based on UNISDR, (2004) and ISO (2009) and explains risk as a function of hazard times consequences. This universal definition of risk has been repeatedly conceptualized within the natural hazard community by Eq. (1) (e.g. Fuchs et al. 2007; Oberndorfer et al. 2007; Bründl et al. 2009). Consequently, the calculation of risk is dependent on a variety of variables all of which being subject to uncertainties (GrêtRegamey and Straub, 2006).

$$R_{i,j} = f(p_j,\ p_{i,j},\ A_i,\ v_{i,j}) \qquad (1)$$

Where $R_{i,j}$ = risk dependent of object $i$ and scenario $j$; $p_j$ = probability of defined scenario $j$; $p_{i,j}$ probability of exposure of object $i$ to scenario $j$; $A_i$ = value of the object $i$ (the value at risk affected by scenario $j$); $v_{i,j}$ = vulnerability of the object $i$ in dependence on scenario $j$.

The valuation of uncertainty in risk assessment is frequently represented by sensitivity analyses to show the effects in varying input values on the results (e.g. Rheinberger et al., 2009). However, the use of confidence intervals allows a discrete calculation of risk with different model setups but does not include probability information. In our study, we quantify the potential uncertainties within road risk assessment based on a case study of a segment of an important mountain road using a stochastic risk assessment approach under consideration of the probability distribution of input data.

## Case study

We applied the probabilistic computation as well as the deterministic standard approach of road risk in a case study. The section of a mountain road in Austria is significantly exposed to a multihazard environment (torrent processes, snow avalanches, rock fall). In Fig. 1 the road segment as well as the hazard areas are displayed which pose a considerably threat for the underlying mountain road both for the road infrastructure and traffic exposed.

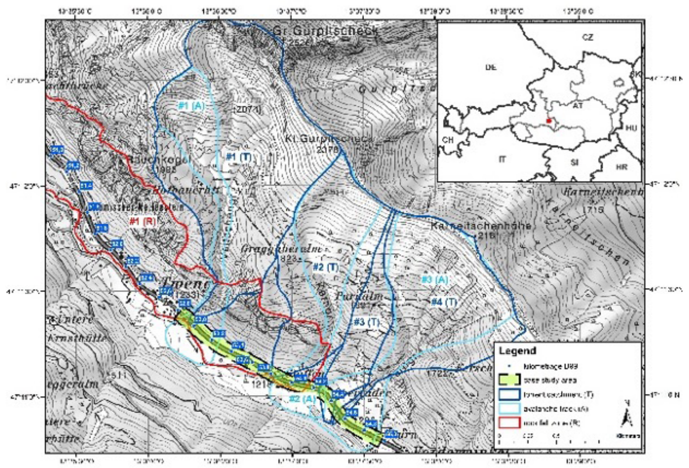

**Figure 1. Overview of the case study area and location of the natural hazards along the road segment dark blue line: four torrent catchments, light blue line: three avalanche paths, redline: one rock fall area. (Source base map: © BEV 2020 – Federal Office of Metrology and Surveying, Austria, with permission N2020/69708).**

## Method

In order to compare the results of the two different risk assessment approaches (deterministic versus probabilistic), we used in a first step the standardized framework from ASTRA (2012) for operational risk assessment for roads and transportation networks and calculated the collective risk RC as a prognostic monetary value per year. RC is commonly defined as the expected annual damage caused by certain hazards and is beside the individual risk RI for exposed persons frequently used as a risk indicator (Merz et al., 2009; Špačková et al., 2014). To compute RC the following three risk categories were considered:

**– Risk for persons RP with three risk situations:**
- Direct impact of the hazard event – standard situation
- Direct impact of the hazard event – specific situation due to traffic jam
- Indirect effect – Rearend collision

**– Property or asset risk RA**

**– Risk due to nonoperational availability or disposability RD**

Using the same formula of the standard approach, we replaced in a second step each individual input data with a probabilistic distribution. The computation of the probabilistic setup was executed with the software RIAAT Risk Administration and Analysis Tool (RiskConsult GmbH, 2016). The probabilistic setup was based on the same equations as the standard approach, but each input variable was processed with a probability distribution instead of a constant or discrete value (point value). Through the consideration of the potential range of input data, the data uncertainty was characterized. The probabilistic setup computed risk by a stochastic calculation technique and aggregated risk with Latin Hypercube (LHS) sampling, which is similar to MonteCarlo simulation (MCS) with the advantage of a faster data processing, a better fitting on the theoretical input distribution and a more efficient calculation as fewer iterations are needed to get equally good results (Sander, 2012). In our simulations we used 1,000,000 iterations to achieve consistent results. The probabilistic setup was carried out with two different and independent simulations each with two different distribution functions. Hence, each variable was modelled using either

**– a triangular or threepoint distribution (TPD) or**

**– a betaPERT distribution (BPD),**

which generated two independent probabilistic setups and results. The risk calculation with two different approaches of probability distributions facilitated a comparison of the applicability and the sensitivity of both simple distribution functions on the results. The expected annual monetary losses induced by the impact of three hazard types (snow avalanches, torrent processes and rock fall) were aggregated and further compacted to the probability density function (PDF) of the collective risk RC. Finally, the two different PDFs from the stochastic risk assessment were compared with the result from the deterministic method to show the potential deviation in the results. For a detailed description of the applied method please refer to Oberndorfer et. al., (2020).

## Results and conclusion

Based on our case study the annual monetary risk is significantly lower if data were computed with the probabilistic framework in comparison to the deterministic standard approach. Thus, without consideration of uncertainty of the input variables risk might be underestimated using the operational standard risk assessment approach for road infrastructure.

The Lorenz curves for the two distributions (TPD and BPD) in Fig. 2 demonstrate the position of the deterministic calculated multihazard risk RC in contrast to the range of the probabilistic risk outcome. Both applied simple distributions (TPD and BPD), show a wide scatter, which can be traced back to the consideration of epistemic uncertainty of the input data. However, the deterministic result is located at the left edge of the Lorenz curve near or below the 5 % percentile (P5).

The Lorenz curves in Fig. 2 refers to the cumulative fraction of the nonexceedance probability of the PDFs of both distributions for modelling input data uncertainty with the advantage of a simplification of result interpretation. Thus, the deterministic outcome of our case study covers approximately less than 5 % of the economic loss which might result in a potential underfunding of 60 k€ (TPD) or 35 k€ (BPD) relating to a conservative chosen benchmark of P95. Both graphs show the degree of deviation due to uncertainties involved in the risk computation. The position of the deterministic result is mainly caused by predominantly rightskewed distributions of the input data, since the aggregation of two right skeweddistributions

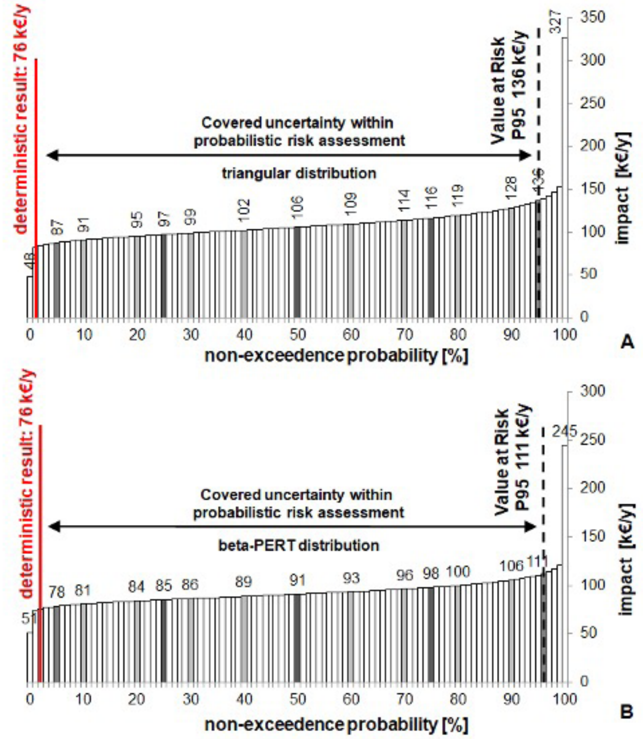


**Figure 2. Lorenz curves for (A) triangular distribution and (B) betaPERT distribution. The graphs show the scale of deviation of the total multihazard risk RC in k€/y within the probabilistic risk modelling in comparison to the deterministic result.**

relocates the deterministic value due to the effect of skewness to the left side of the resulting distribution. The effect is strongly depended on the extent of the positive distribution skewness.

The degree of uncertainty can be captured by an appropriate choice of a ValueatRisk (VaR) level. For example, the 95 % quantile (P95) of the PDF covers 95 % of the potential uncertainties within the risk calculation. However, a suitable VaR level is depended on many external factors such as the general safety requirement of the system, political and legal requirements, engineering guidelines and codes as well as on the scale of uncertainty of the input data. Especially the last point requires a high expert knowledge to draw the right conclusions of the data interpretation.

## Discussion

The results based on our case study have shown that risk is underestimated if computed with common deterministic approaches in comparison to probabilistic approaches, mainly due to epistemic uncertainties of the parameter spectrum. Thus, the full spectrum of potential road risk is not adequately covered using the standard approaches, which may lead to a decision bias on risk mitigation measures. For robust riskbased decisionmaking, we therefore recommend the use of probabilistic risk assessment (PRA) due to the consideration of a greater range of possible uncertainties. This fosters a general increase in information for road authorities and political decisionmakers and facilitates transparent economic decisions for the implementation of mitigation measures against natural hazards. The advantages of PRA in comparison to conventional risk analysis can be summarized as follows:

- The input data for consequence and for the probability of occurrence are no longer single values without uncertainty representation but probability distributions with at least minimum, most likely, and maximum value to shape a simple distribution, and therefore uncertainty is explicitly included.

- The results are not point values from the mathematical addition of likelihood and consequences rather PDFs generated by stochastic simulation with MCS or LHS. Therefore, a bandwidth (range) of aggregated risk is computed based on a wide number of coincident but realistic scenarios, which provides an explicit consideration and treatment of the reducible (epidemic) uncertainty.

- The results are displayed as PDF allowing a VaR interpretation for each value (quantiles) within the bandwidth instead of a single sharp number without an associated probability.

However, the choice of a robust risk value for natural hazard decision as an acceptable quantile of the PDF is a challenging task. In our opinion, a ValueatRisk (VaR) approach through the consideration of a reliable nonexceedance probability is an appropriate concept for this challenge. Generally, a higher level of the nonexceedance threshold yields in a higher system safety for transportation corridors. Since an appropriate safety level is a balance between technical feasibility, social acceptance, and political implementation, which is strongly dependent on the underlying legal framework, a PDF may support decisionmakers to achieve betterinformed decisions.
Our probabilistic risk assessment approach allows the quantification of uncertainty, and in turn allows decision makers to better assess the quality and validity of road risk computation. Thus, PRA generates an important increase in information, which is fundamental for optimal riskbased decisionmaking under budget constraints. This facilitates an increase of knowledge about potential road risk with the effect of a better informed and transparent basis for implementing risk minimization measures for roadsafety authorities, design engineers and policy makers.

As a consequence of our study and considering the limitations we recommend following further research initiatives:

- Increasing research on vulnerability/lethality thresholds for road infrastructure and traffic to get hazard and objectspecific vulnerability/lethality functions as these factors are attributed to a high degree of uncertainty. These vulnerability/lethality functions should be either based on detailed event documentation or on physical impact assessments.

- Further research on suitable probability distributions to represent risk variables since the scale of deviation is dependent on the choice of distribution for modelling the bandwidth of input data. However, if there is little to none empirical evidence on the distribution of input data (e.g. estimation from experts), simple distributions such as a TPD or a BPD can adjust the shape of the distribution better than complex distributions. Hence, the use of complex distributions for a prognostic risk prediction with a lack of empirical data cannot be justified.

- Consideration of probabilistic hazard analyses to enable a holistic PRA for natural hazards. In our study the hazard analyses were an outcome of prior technical studies for the regional road authority of the federal state.

- Development of guidelines for the treatment of uncertainty information for decisionmakers (authorities, engineers, politicians). We recommend the VaR approach as this is a standard approach in economic and technical risk assessment.

- Consideration of probabilistic methods also for budgeting of safeguarding, as the results of a monetary risk assessment are frequently compared to the costs of mitigation measures to achieve an optimal riskbased design using a cost benefit analysis. Since cost assessments of mitigation measures are subject to considerably uncertainties, especially at the beginning of the planning process where information is limited, a probabilistic assessment of defence structures is recommended using the same benchmark value of the VaR.

Even though the presented methodology for our casestudy is based on a road segment exposed to a multihazard environment on a localscale, the approach can easily be transferred to other scales and other assessments for naturalhazard risk.

## References


ASTRA (2012): Naturgefahren auf Nationalstraßen: Risikokonzept, Methodik für eine risikobasierende Beurteilung, Prävention und Bewältigung von gravitativen Naturgefahren auf Nationalstraßen, Bundesamt für Straßen ASTRA, Bern.

Bründl M. (Ed.) (2009): Risikokonzept für Naturgefahren – Leitfaden. Nationale Plattform für Naturgefahren PLANAT, Bern, 2009.

Bründl, M., Ettlin, L., Burkard, A., Oggier, N., Dolf, F. und Gutwein, P. (2015): EconoMe – Wirksamkeit und Wirtschaftlichkeit von Schutzmaßnahmen gegen Naturgefahren, Formelsammlung.

Fuchs, S., Heiss, K., Hübl, J. (2007): Towards an empirical vulnerability function for use in debris flow risk assessment, Nat. Hazards and Earth Syst. Sci., 7, 495–506, https://doi.org/10.5194/nhess74952007.

International Organisation for Standardisation (2009): Risk management – Principles and guidelines on implementation, ISO 31000, Geneva.

Merz, B., Thieken, A. H.: Flood risk curves and associated uncertainty bounds, Nat. Hazards, 51, 437–458, https://doi.org/10.1007/s1106900994526, 2009.

Oberndorfer, S., Fuchs, S., Rickenmann, D., Andrecs, P. 2007): Vulnerabilitätsanalyse und monetäre Schadensbewertung von Wildbachereignissen in Österreich, Bundesforschung und Ausbildungszentrum für Wald, Naturgefahren und Landschaft, BFWBerichte 139/2007, Wien.

Oberndorfer, S., Sander, P., and Fuchs, S. (2020): Multihazard risk assessment for roads: Probabilistic versus deterministic approaches, Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess202066, in review.

PapathomaKöhle, M., Gems, B., Sturm, M., Fuchs, S. (2017): Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flow, EarthSci. Rev. 171, 272288, https://doi.org/10.1016/j.earscirev.2017.06.007.

RiskConsult GmbH: RIAAT Risk Administration and Analysis Tools, Manual, Version 28F01, Innsbruck, 2015.
Sander, P. (2012): Probabilistische RisikoAnalyse für Bauprojekte. Entwicklung eines branchenorientierten softwaregestützten RisikoAnalyseSystems, University of Innsbruck, ISBN 9783902811752.

Špačková, O., Rimböck, A., Straub, D.: Risk management in Bavarian Alpine torrents: a framework for flood risk quantification accounting for subscenarios, in: Proc. of the IAEG Congress 2014, IAEG XII congress, Torino, Italy, 2014.

UNISDR (2004): Living with risk: A global review of disaster reduction initiatives, United Nations Publication, Geneva.