We thank the referee #1 for their time to go through our manuscript and for the insightful and useful comments to improve our manuscript. Below we chronologically list the questions of the referee - referee comment (RC) and our answers - author comments (AC):

Specific comments:

RC1: Suggestion: Extend the start of the introduction; line 25-32. Identify and describe the gaps that this paper is addressing. Introduce a new main section called Background; containing the subsections "Multi-hazard risk assessment", "Deterministic risk concept", "Uncertainties within risk assessment" and "Deterministic vs. probabilistic risk". Include/Move the "Objective" subsection before the suggested "Background section".

AC1: We followed your suggestion and structured the article accordingly. We introduced a background section and extended the introduction section.

RC2: Line 12-13: "Due to a variety of variables and data needed for risk computation, a considerable degree of epistemic uncertainty results." : Please clarify this sentence. Why do the need for a variety of variables and data lead to epistemic uncertainty?

AC2: We revised this part of the abstract to make it more understandable.

Abstract. Mountain hazard risk analysis for transport infrastructure is regularly based on deterministic approaches. Standard risk assessment approaches for roads need a variety of variables and data for risk computation, however without considering potential input data uncertainty. Consequently, input data needed for risk assessment is normally processed as discrete mean values without scatter, or as an individual deterministic value from expert judgement if no statistical data is available. To overcome this gap, we used a probabilistic approach to analyse the effect of input data uncertainty on the results, taking a mountain road in the Eastern European Alps as case study. The uncertainty of the input data is expressed with potential bandwidths using two different distribution functions. The risk assessment included risk for persons, property risk and risk for non-operational availability exposed to a multi-hazard environment (torrent processes, snow avalanches, rock fall). The study focuses on the epistemic uncertainty of the risk terms (exposure situations, vulnerability factors, monetary values) ignoring potential sources of variation within of hazard analysis. Reliable quantiles of the calculated probability density distributions attributed to the aggregated road risk due to the impact of multiple-mountain hazards were compared to the deterministic results from the standard guidelines on road safety. The results based on our case study demonstrate that with common deterministic approaches risk might be underestimated in comparison to a probabilistic risk modelling setup, mainly due to epistemic uncertainties of the input data. The study provides added value to further develop standardized road safety guidelines and may therefore be of particular importance for road authorities and political decision-makers.

RC3: Line 14-16: "To overcome this gap, we used a probabilistic approach to express the potential bandwidth of input data with two different distribution functions, taking a mountain road in the Eastern European Alps as case study." a) A bit unprecise formulation, I think. A Probabilistic approach is applied to analyse how the uncertainty in the input data affects the result. The uncertainty in the input data is expressed with a potential band width and two different distribution functions. b) It should also be specified, in general terms for which type of input data uncertainty is included (e.g. exposure, vulnerability and monetary values) and for which they are not included (e.g. hazard C2 NHESSD Interactive comment Printer-friendly version Discussion paper intensities).

AC3: We clarify this in the abstract.

RC4: Line 16-18: " The risk assessment included the damage potential of road infrastructure and traffic exposed to a multi-hazard environment (torrent processes, snow avalanches, rock fall). : Refer to terms used later in document: Risk for persons, Property risk and Risk for operational availability

AC4: We clarify this in the abstract.

RC5: Line 21-22: "The results demonstrate that with common deterministic approaches risk is underestimated in comparison to a probabilistic risk modelling setup, mainly due to epistemic uncertainties of the input data." : This conclusion is very surprising. It should be clear that this is only valid for the current study and not generally valid when comparing deterministic and probabilistic results. Usually, conservative values for the input parameters are applied in a deterministic approach to account for the uncertainties – and to provide conservative results. Alternatively, the expected value of the input parameters could be used and the results from the deterministic approach would give the expected value from the probabilistic approach. The validity and explanations for this conclusion should be discussed in the paper.

AC5: We clarify this in the abstract and extended the discussion with this paragraph: Even if conservative risk values are used in a deterministic setup, a potential scatter (upper and lower bounds) remains, which leads within a probabilistic calculation through aggregation of the partial risk elements and sub-results to a right-skewed distribution according to the skewness of input variables. Since risk values of our study are in most cases asymmetric with primarily positive skews, the deterministic result migrates during aggregation to the left side of the PDF.

RC6: Line 22-23: "The study provides added value to further develop standardized road safety guidelines and may therefore be of particular importance for road authorities and political decision-makers. : Include in the discussion some thoughts on the application of the results, e.g. how could information about uncertainty in the results be applied within future work to improve the current road safety guidelines.

AC6: We already discussed the applicability for improvement road safety guidelines. We gave an additional example for further improvement by implementing a VaR concept to include more information for decision making on road safety issues.

RC7: Line 32: "In contrast, there is still a gap in multi-hazard risk assessments for road infrastructure." a) In which way is this paper also addressing this gap? b) I suggest also to include some introducing text, identifying gaps regarding treatment of uncertainty, to motivate for the coming sub-sections on the topic c) Are there special challenges regarding uncertainties for multi-hazard assessment?

AC8: We clarified this issue and structured the introduction accordingly.

RC8: Line 151-159 "Objective" a) The content of the "Objective" subsection should address the scope of the study, referring to the identified gaps described in the introduction, i.e. both related to multi hazard assessment and treatment of uncertainties. b) Include: is the multi-hazard risk method in this paper a spatially oriented and a thematicallydefined method.

AC8: We followed your suggestion and structured the article accordingly. We introduced a background section and extended the introduction section.

RC9: Line 217-219: "Due to the catchment characteristics of the torrents two different indicator processes were assigned for assessing the hazard effect, depending on the two occurrence intervals. Therefore, the occurrence interval served as a proxy for the process type." : I didn’t understand this. Could you please clarify/give an example?

AC9: To clarify this in more detail we changed the sentence into: “Therefore, the occurrence interval served as a proxy for the process type since we assumed for the frequently occurring events (p = 0.1) the hazard type “flash floods with sediment transport” and for the medium scale recurrence intervals (p = 0.033) debris flow processes.”

RC10: Line 213- 224: : Should some of the content be moved to the description of the case study area?

AC10: In the revised version of the document we moved the sentence: “As shown in Fig. 2, the road segment is affected by three avalanche paths, four torrent catchments and one rockfall area.” As well as the passage “The four torrent catchments have steep alluvial fans on the valley basin. The road segment is located at the base of these fans or the road is slightly notched in the torrential cone and passes the channels either with bridges or with culverts. The rockfall area is situated in the west district of the road segment (Fig. 2). Approximately two third of the study area is affected from rock fall processes either as single blocks or by multiple blocks.” to the study area chapter.

RC11: Line 301-302: "These values were either defined from statistical data, expert judgement or from existing literature." : As these values are important for the results; some more documentation on how they were chosen or found should be included, i.e which statistics, literature is applied – or what is the reasoning behind the expert judgment.

AC11: In the Appendix Tables A6 to A9 the source of each variables is quoted in Tables A6 to A9 in the Appendix. We extended the quotation for l / m / u bounds in the source column. The choice of the variable range in Tables A6 to A9 in the Appendix is case study specific and cannot be transferred to other studies without careful validation.

RC12: Line 335 -337: " In reality, risk parameters commonly have a natural boundary. Therefore, estimating min/max values instead of standard deviation is more realistic or feasible as there is in most cases no data available to express the mean variation. : Justify the use of natural boundaries in this context and what the natural boundaries of risk parameters could be; f.ex. Vulnerability is always between 0 and 1. However; why would there be other natural upper boundaries than 1 in vulnerability; for specific intensities?

AC12: We supplemented the text with an example of vulnerability factors with boundaries ranging from 0 (no loss) to 1 (total loss).

RC 13: Appendix: Tables A6 – A9 : Explain symbols for non-SI units (d, y, n, etc.)

AC13: The symbols for non-SI-Units will be explained and added in the headings of each table in the revised version of the manuscript.

We kindly would like to thank referee #2 for his/her efforts to evaluate our manuscript and for the insightful and useful comments. Below we chronologically list the questions of the referee – referee comment (RC) and our answers – author comments (AC):

2 Specific comments

2.1 Multi-hazard risk assessment

(RC1): The section of multi-hazard risk assessment is very short and therefore only addresses some aspects of this complex topic. I would have expected that this section would show more clearly where are the main gaps and how this paper addresses these gaps. The last sentence targets the difference of results of deterministic vs probabilistic approaches and would therefore fit better in one of the following paragraphs.

(AC1): We have deliberately kept this paragraph short and only focused on multi-hazard risk assessment for roads. We cited relevant publications of different hazard processes associated with road risk in the introduction. However, we will restructure the introduction in a revised version of the manuscript so that the overall gap that will be addressed in the manuscript becomes clearer.

2.2 Deterministic risk concept

(RC2): In the paragraph lines 75–83 please explain the inconsistencies you mention (line 79–80). What means inconsistent in this context?

(AC2): We will change the term inconsistencies with "*bias*" and will add *"(either over- or underestimation dependent on the scale of input variables)*" to make this sentence clearer.

(RC3): You are right that papers quantifying uncertainties are underrepresented and you cite a paper from 2006. However, meanwhile there are probably much more available. To name only a few, which come to my mind (may be only to show what's missing):

- Rheinberger, C.M., Bründl, M. and Rhyner, J. (2009) Dealing with the White Death: Avalanche Risk Management for Traffic Routes. Risk Analysis 29(1), 76-94.
- Schaub, Y. and Bründl, M. (2010) Zur Sensitivität der Risikoberechnung und Massnahmenbewertung von Naturgefahren. Schweizerische Zeitschrift für das Forstwesen 161(2), 27-35.
- Bründl, M. (2012) EconoMe-Develop - a software tool for assessing natural hazard risk and economic optimisation of mitigation measures. International Snow Science Workshop ISSW, Anchorage, Alaska, pp. 639-643.

If you have done an extensive search on this aspect, it's ok; otherwise I would appreciate to see some papers on uncertainty assessment cited

(AC3): In the current manuscript version, we cited relevant literature in the section "Uncertainties within risk assessment" and we agree that the paper mentioned by the referee is a bit outdated. We will update the text body with newest scholarly works so that the sentence could read as follows: *"Therefore, loss assessment for natural hazard risk is associated with high uncertainty (Špačková et al., 2014 and Špačková, 2016) and studies quantifying uncertainties of the expected consequences are underrepresented (Grêt-Regamey and Straub, 2006), especially regarding natural hazards impacts on roads (Schlögl et al., 2019). For the assessment of an optimal mitigation strategy for an avalanche-prone road Rheinberger et al. (2009) considers parameter uncertainty by assuming a joint (symmetric) deviation of ±5% for all input values to construct a confidence interval for the baseline risk. The assessment of uncertainty of natural hazard risk is therefore frequently represented by sensitivity analyses to show the sensitivity of a shift in input values on the results. Thus, the use of confidence intervals allows a discrete calculation of risk with different model setups. In our study, we quantify the potential uncertainties within road risk assessment using a stochastic risk assessment approach by consideration of the probability distribution of input data".*

2.3 Deterministic vs. probabilistic risk

(RC4): I think, in this section different aspects are discussed, which are not necessarily related to a comparison of deterministic vs probabilistic approaches. I suggest to structure it more clearer. You write in line 126 “. . . a defined value (point value) for probability . . . In my experience, return period intervals, e.g. for a 1 on 10 - 30 years event, are used. Are these point values?

(AC4): We thank the referee for this valuable comment. Obviously, the content can be misunderstood, so, in a revised version of the manuscript we will restructure the chapter. The return periods are intervals, but they are mathematically addressed as point values. In our study we only focused on frequent events a 1 in 10 year event and a 1 in 30 year event. In both concepts the probability of occurrence was treated as point values. We totally agree that in a fully probabilistic concept also the probability of occurrence should also be expressed in a probabilistic way. However, since the hazard analysis (with deterministic design events to assess the hazard intensities as a function of the return interval) was part of prior technical studies, further considerations were outside of the study design. This topic might be addressed in a subsequent study.

We will also address this limitation in the conclusion as follows: “*Thus, the probability of occurrence of the hazard processes was mathematically processed as point value within the probabilistic design since the hazard analyses (with deterministic design events to assess the hazard intensities as a function of the return interval) was part of prior technical studies. Further considerations of a probabilistic modelling of the frequency of the events were outside of the study design and might be addresses in subsequent studies”.*

(RC5): In line 127–129 you write that risk from multiple risks are summed up, which result in an expected average loss. Despite that the term “individual risk” is usually used for the risk an individual person is exposed to (below or above a threshold), this depends how risk is depicted from different processes. Risk can be depicted for each of the processes and for each of the return period intervals (if we speak of return period, which is not the case for non-returning processes such as rockfall). Also the next topic in the bullet point list (“high probability-low consequence . . . ”) is not necessarily a topic of a deterministic vs. a probabilistic approach but of weighting, which is known as risk aversion affect (which is controversially discussed especially in the natural hazard community). In the third bullet point, the term “Value at Risk” is mentioned, which should be better explained. Overall, I have the impression that different aspect are mixed and could be structured better.

(AC5): We agree and will change the term “individual risk” to “single risk” to prevent possible misinterpretation with respect to collective versus individual risk (risk of persons).

We will further extend the first bullet point with the risk aversion discussion as follows:

“*A deterministic method gives equal weight to those risks that have a low probability of occurrence and high impact and to those risks that have a high probability of occurrence and low impact by using a simple multiplication of probability and impact, a topic which is also known as risk aversion affect and controversially discussed in the literature (e.g., Wachinger et al, 2013, Lechowska, 2018)”.*

We will also extend the last bullet point with an explanation of the value at risk as follows: “*The VaR is a measure of risk in economics and describes the probability of loss within a time unit, which is expressed as a specified quantile of the loss distribution (Cottin and Döhler, 2013)”.*

In table 1 some things are unclear to me:

(RC6): First row: you write that in a probabilistic assessment of risk one number for the probability of occurrence is required. Deriving the probability of occurrence as part of the hazard analysis is a very critical for a risk analysis if not the most important. In my opinion, the largest uncertainty is probably here (see Schaub and Bründl, 2010, citation above) and a probabilistic method should therefore also handle the uncertainty of the probability of occurrence in order to be really probabilistic. May be you could mention this somewhere in the introduction; its mentioned at the end of the conclusion section.

(AC6): We totally agree with that but we did not model the probability of occurrence in our study in a probabilistic way. In the reversed version of the manuscript we will additionally mention this in the introduction and in the conclusion as you intended to make this more understandable for the readers.

In the introduction we will address this as follows: *"Thus, the probability of occurrence of the hazard event was not assess in a probabilistic way. Since deriving the likelihood of occurrence as part of the hazard analysis is crucial for risk analysis, a high source of uncertainty is attributed to this factor (Schaub and Bründl, 2010)"*.

We will expand this sentence in table 1 as follows: "*The probabilistic assessment of risk requires at least one number or – for an entirely probabilistic modelling – a PDF for the probability of occurrence and several values for the impact (e.g., minimum, most likely and maximum) expressed as distribution functions, therefore including uncertainty"*.

(RC7): Second row: Mathematical addition in deterministic method: this depends how you aggregate and depict the risks. It is not necessarily the way you describe it here. Upper and lower boundaries are possible.

(AC7): That's correct, but usually in deterministic risk assessments risk is calculated with standard (single values) and the calculation can bei supplemented with upper and lower bounds to show the sensitivity of the input on the results. This is mostly done by a sensitivity analysis with different model setups which are per se deterministic calculations. This differs from probabilistic analysis where each input variable is treated with a distribution.

We will extend the row with this sentence: "*The deterministic calculation can bei supplemented with upper and lower bounds (different model setups) to show the sensitivity of the input on the results using a sensitivity analysis, which are per se separate deterministic calculations"*.

(RC8): Third row: To my knowledge, the result of a risk analysis is risk, expressed either in monetary terms per time unit, e.g. Euro per year or number of fatalities or injured persons per year. If you differentiate different scenarios, e.g. occurrence probability 0.1, 0.033, etc., you'll get several numbers, which however can be added following conventions (e.g. cumulative-complementary probability).

(AC8): We are sorry for this confusion, the referee is right. We will clarify this by including an exemplifying statement such as "*(monetary value or fatality per time unit)"* and will further address this issue in the bullet points.

(RC9): In figure 1 the differences between probabilistic and deterministic approach does not become clear to me. The way, risk is calculated is the same, but for the probabilistic approach with a distribution of a parameter, whereas in a deterministic approach, a single parameter is used. This is not clearly shown in the graph. Instead of "Process specific risk classes" you could name the column processes and process areas. What does not come out, how risk from individual process areas are handled (added). In the upper left graph (PDF) the unit "kEuro" for impact represents "risk", right? Then the unit should be "kEuro/year". See also comments below.

(AC9): Thanks for this important comment. We will change the unit for PDF in the figure to *k€/y* and exchange Process "specific classes" with "*hazard processes*". Moreover, we will explain the flow chart in the figure caption in more detail as follows: *"Figure 1. Exemplified flow chart for the risk assessment method following the standard approach (deterministic risk model) from ASTRA (2012) which was supplemented with the probabilistic risk model in present study. In the deterministic approach each risk variable is addressed with single values and the specific risk situations are summed up to risk categories for each hazard process class and scenario (probability of occurrence of the hazard process) and finally to the collative risk, whereas the* *probabilistic setup uses a probability distributions to characterize each risk variable and further aggregates risk by stochastic simulation to the total risk".*

2.4 Hazard analysis (section 3.1)

(RC10): In line 189 you probably mean by "potential hazards" potential release areas which serve as input for the numerical simulation. In line 201, I suggest to replace "expression" by "extent".

(AC10): Thank you for this comment. We will change the wording from "potential hazards" to "*potential hazard sources*" and replace "expression" by "*extend*".

(RC11): In the lines 217–219 it's not clear to me what you want to say. I suggest to rephrase these sentences. In line 223, you might want to replace "west district" by "western part".

(AC11): We will rephase the sentences in accordance with the comments of referee #1 to: "*Due to the catchment characteristics of the torrents two different indicator processes were assigned for assessing the hazard effect, depending on the two occurrence intervals. Therefore, the occurrence interval served as a proxy for the process type since we assumed for the frequently occurring events (p = 0.1) the hazard type "flash floods with sediment transport" and for the medium scale recurrence intervals (p = 0.033) debris flow processes."*

We will also replace "west district" into "*western part*" and move this paragraph to the case study section as recommended by referee #1.

2.5 Standard guideline for risk assessment (section 3.2)

(RC12): I suggest to explain somewhere how you separate the object of risk affected by one or several processes in the different scenarios. What are the objects? Road sections C5 affected by one single hazard?

(AC12): Thank you for this comment, we will give explanations of potential affected objects in a revised text, such as *"(affected road segment, culverts, bridges etc.)"*.

(RC13): In the lines 254–255 you describe the monetization of fatalities. Please briefly mention the approach (I assume by "value of statistical life (VSL)") and the value. Although it can be found in the annex, it would be helpful here.

(AC13): We will change the sentence to better focus on the used approach as follows: "*The published average national expenses of road accidents include materially and immaterially costs (body injury, property damage and overhead expenses) of road accidents and are based on statistical evaluations of the national database as well as on the willingness to pay approach for human suffering. The monetized costs for a statistical human life equal 3 M€".*

(RC14): In the lines 257–259 you give the link to the equations how risk is calculated. Please carefully check the equations for the correct denominations, especially calculation of collective vs. individual risk (see comment below).

(AC14): We will check the equation carefully. In our study, however, we focused on the collective risk and excluded the individual risk of highly exposed persons.

2.6 Results and Discussion

(RC15): I have some problems interpreting the results. Experiences in practice indicate that risk is overestimated compared to real-case events with accidents. In your study you show that deterministic risk analysis underestimates the risk compared to the probabilistic analysis. For me, it becomes not clear why this is the case. The reason could be that the standard value of an input parameter is much too low and the "real" distribution of this input parameter is left skewed (median values are higher than the mean values). But how you know the right distribution?

(AC15): We used two different simple distribution (BPD and TPD) for modelling the bandwidth of each parameter since the actual right distribution of values is not known. We think this is a practical approximation to model a scatter of input data. If more data and research for example for vulnerability or lethality values is available, other more complex distributions may replace these simple distributions.

In the current version of our manuscript we addressed the underestimation of risk in our case study in accordance with the comments of referee #1 as follows: "*Hence, the multiplication of two positive symmetrical distributions results in a right-skewed distribution, because the product of the small numbers at the lower ends of the bandwidths results in much smaller numbers than the product of the high numbers at the upper ends of the bandwidths. When right-skewed distributions are used as input and aggregated, the effect of skewness shifts the deterministic value (represented by the most likely value) to the right side of the resulting distribution.*

Even if conservative risk values are used in a deterministic setup, a potential scatter (upper and lower bounds) remains, which leads within a probabilistic calculation through aggregation of the partial risk elements and sub-results to a right-skewed distribution according to the skewness of input variables. Since risk values of our study are in most cases asymmetric with primarily positive skews, the deterministic result migrates during aggregation to the left side of the PDF in Fig. 5".

(RC16): What would be helpful for the reader is to better explain the meaning of "Value At Risk" (see comment above). Choosing a higher Value-At-Risk-Level (in this case 95% nonexceedance probability) would mean a higher safety level. May be you could write some words more about this concept.

(AC16): We will explain the VaR concept (see above) in section 2.4 and complement the VaR in the Conclusion section as recommended by the referee as follows: "*In this context, a higher VaR value implies a higher safety level for the system under investigation".*

(RC17): In Figure 3, Table 3, Figure 4 and 5, I see some inconsistencies regarding the units (see also comment above). All numbers which depict risk should have the unit k per year, so deterministic risk (clearer than "result") and also the "Value At Risk". In Figure 4 and Table 3 I suggest to use the same description of processes. In Table 3 percentages should sum up to 100% (or least close to, which is a problem of rounding of numbers).

(AC17): Thank you for this very important observation. We will change the unites to k€/y in every figure accordingly. In the caption of table 1 we will add to the explanation that "*risk-based aggregated losses do not equal the sum of the sub-components because probabilistic metrics such as P50 are not additive. Thus, the computational sum as well as the percentage are slightly different".*

(RC18): As mentioned above, the right-skew in Figure 4 is not clear in relation to the distribution of the input parameters.

(AC18): Please see our comments to RC15.

(RC19): For figure 5, I suggest the same scale for both x-axes so that results can be better compared.

(AC19): Unfortunately, due to the classes of the frequency plot the scale of the x-axes cannot be changed.

(RC20): At the end of this section, you discuss some consequences of your work for practice. It might be helpful to discuss the consequences of dealing with these uncertainties for practice. Discussions with risk experts reveal that they are aware of uncertainties in input parameters, but it is often not clear how to deal with these results, when uncertainties are explicitly assessed? Communication in practice is very critical in this respect especially to end users such as stakeholders in authorities and communities. What would this mean in regard to the allocation of public money for mitigation measures? Following your argumentation, we could argue that societies in most countries spend too less money for mitigation measures. I think it would be worth to say that your result are the consequences of the chosen distribution of the input values (e.g. upper bounds determined by experts). May be you can add some sentences addressing these aspects.

(AC20): Thank you very much for this comment. We will address these issues throughout a revised version of the manuscript, and we will particularly extend this discussion at the end of this section, such as:

“*In this context, a higher VaR value implies a higher safety level for the system under investigation. The final results are subject to uncertainties mainly due to insufficient data basis of input variables, which can be addressed using a PDF to represent uncertainties involved. For further decisions on the realization of mitigation measures a high VaR value such as P95 covers these uncertainties with a defined shortfall probability and thus supports decision makers with more information of road risk. In turn, as a further practical improvement this benchmark can be compared to the same grade of safety for the costs of mitigation measures since cost assessments for defence structures are also subject to considerable uncertainties. Thus, an optimal risk-based design of defence structures might encompass a balance between the same VaR level both of a probabilistic risk and a probabilistic cost assessment utilizing a cost benefit analysis (CBA)”.*

Technical corrections

(RC21): Line 43: reference to table 2 does not fit here; Please check the order of the table and their numbering.

(AC21): We will check this and correct, if necessary.

(RC22): Line 186: “The hazard analysis was conducted in technical studies”*!* “The hazard analysis was part of technical studies”.

(AC22): We will change this according to your recommendation.

(RC23): Appendix: Please carefully check the equations for the correct denominations, especially calculation of collective vs. individual risk, e.g. Table A1: If you calculate the risk of a person i in scenario j, this would the individual risk; therefore C7 NP in equation 1A would be 1.

(AC23): Thank you very much for this comment. We will fix all headings and descriptions.

(RC24): Table A4: would is the meaning of l in equation 4A?

(AC24): l means the length of the affected road section. We will add the description.

(RC25): Equation 5A: you probably mean pj instead of pi?

(AC25): Thank you very much, we will change this expression accordingly.

(RC26): Table A7: I suggest to use the correction term for CP: it is the value of statistical life (VSL) (?).

(AC26): We will check and provide explanation in a revised version of the manuscript.

(RC27): Table A9: variable $CRb;W$ = expenses?

(AC27): Thank you very much, we will correct this variable description.

Multi-hazard risk assessment for roads: Probabilistic versus deterministic approaches

Stefan Oberndorfer[1,2], Philip Sander[3], Sven Fuchs[2]

[1]Chartered Engineering Consultant for Mountain Risk Engineering and Risk Management, Ecking 57, 5771 Leogang, Austria
[2]Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences, Peter Jordan Straße 82, 1190 Vienna, Austria
[3]Institute of Construction Management, Bundeswehr University Munich, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany

Correspondence to: Stefan Oberndorfer (office@oberndorfer-zt.at)

Abstract. Mountain hazard risk analysis for transport infrastructure is regularly based on deterministic approaches. Standard risk assessment approaches for roads need a ~~Due to a~~ variety of variables and data ~~needed~~ for risk computation, however without considering potential uncertainty in the input data. ~~, a considerable degree of epistemic uncertainty results.~~ Consequently, input data needed for risk assessment is normally processed as discrete mean values ~~with or~~ without scatter, or as an individual deterministic value from expert judgement if no statistical data is available. To overcome this gap, we used a probabilistic approach to analyse the effect of input data uncertainty on the results, taking a mountain road in the Eastern European Alps as case study. The uncertainty of the input data is expressed with potential bandwidths using two different distribution functions. ~~express the potential bandwidth of input data with two different distribution functions, taking a mountain road in the Eastern European Alps as case study.~~ The risk assessment included ~~the damage potential of road infrastructure and traffic~~ risk for persons, property risk and risk for non-operational availability exposed to a multi-hazard environment (torrent processes, snow avalanches, rock fall). The study focuses on the epistemic uncertainty of the risk terms (exposure situations, vulnerability factors, monetary values) ignoring potential sources of variation in the hazard analysis. As a result, ~~R~~reliable quantiles of the calculated probability density distributions attributed to the aggregated road risk due to the impact of multiple-mountain hazards were compared to the deterministic ~~results~~ outcome from the standard guidelines on road safety. The results based on our case study demonstrate that with common deterministic approaches risk ~~is~~ might be underestimated in comparison to a probabilistic risk modelling setup, mainly due to epistemic uncertainties of the input data. The study provides added value to further develop standardized road safety guidelines and may therefore be of particular importance for road authorities and political decision-makers.

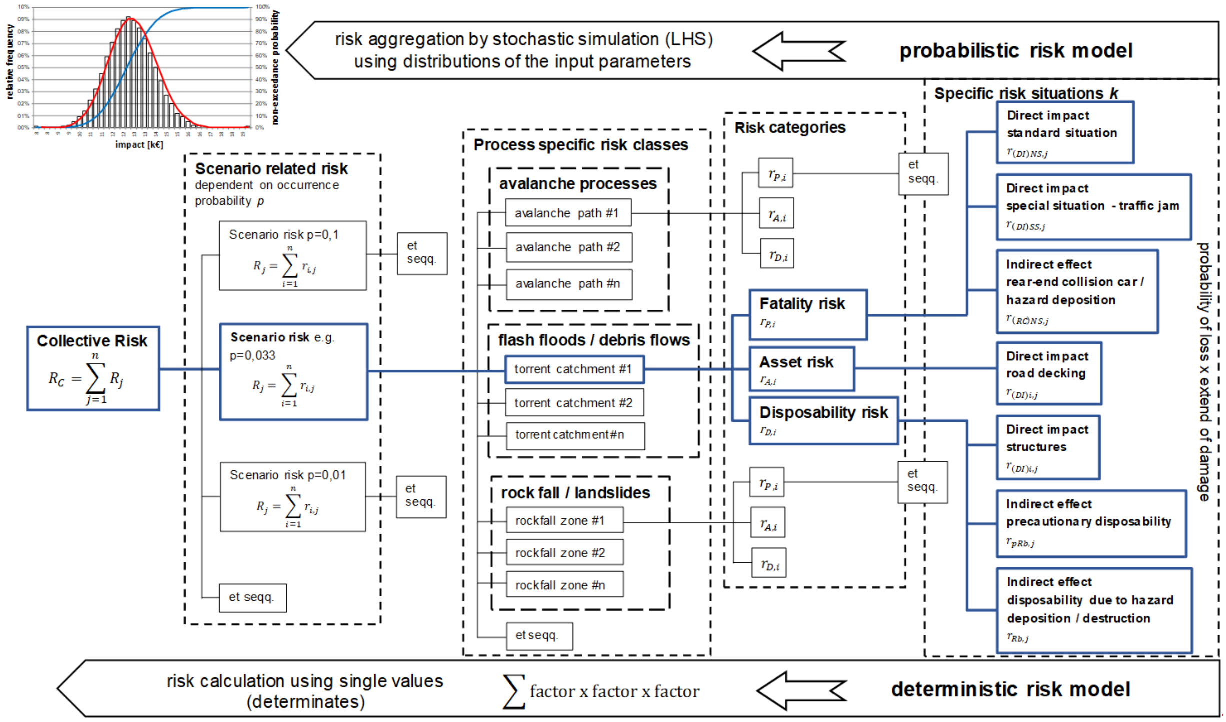
1 Introduction

Mountain roads are particularly prone to natural hazards, and consequently, risk assessment for road infrastructure focused on a range of different hazard processes, such as landslides (Benn, 2005; Schlögl et al., 2019), rockfall (Bunce et al., 1997; Hungr and Beckie, 1998; Roberds, 2005; Ferlisi et al., 2012; Michoud et al., 2012; Unterrader et al., 2018) and snow avalanches (Schaerer, 1989; Kristensen et al., 2003; Margreth et al., 2003; Zischg et al., 2005; Hendrikx and Owens, 2008; Rheinberger et al., 2009; Wastl et al., 2011). These studies have in common that they exclusively address the ~~negative ~~interaction of individual hazards with values at risk of the built environment and/or of society and use qualitative, semi-quantitative and/or quantitative approaches. ~~In contrast~~However, there is still a gap in multi-hazard risk assessments for road infrastructure.

~~Objective~~

The article provides a comparison of a standard (deterministic) risk assessment approach for road infrastructure exposed to a multi-hazard environment with a probabilistic risk analysis method to show the potential bias in the results. The multi-hazard scope of the study is based on a spatially--oriented approach to include all relevant hazards within our study area. Using this approach, we address the consequences of multiple hazard impact on road infrastructure and compare the monetary loss of the different hazard types. The standard framework from ASTRA (2012) for road risk assessment is based on a deterministic approach and computes road risk based on a variety of input variables. Data is generally addressed with single values without considering potential input data uncertainty. We used this standardized framework for operational risk assessment for roads and transportation networks and supplemented this~~e~~ well-established deterministic method with a probabilistic framework for risk calculation (Fig. 1). A probabilistic approach enables the quantification of epistemic uncertainty and uses probability distributions to characterize data uncertainty of the input variables while a deterministic computation uses single values with discrete values without uncertainty representation. While the former calculates risk with constant or discrete values, ignoring the epistemic uncertainty of the variables, the latter enables the consideration of the potential range of parameter value by using different distributions to characterize the input data uncertainty. Our study focuses on the epistemic uncertainty of the risk terms (exposure situations, vulnerability factors, monetary values) ignoring potential sources of variation within hazard analysis. Thus, the probability of occurrence of the hazard event was not assessed in a probabilistic way. Since deriving the likelihood of occurrence as part of the hazard analysis is crucial for risk analysis, a high source of uncertainty is attributed to this factor (Schaub and Bründl, 2010). ~~Even though the presented methodology in this study focuses on a road segment exposed to a multi-hazard environment on a local-scale, the approach can easily be transferred to other risk-oriented purposes. ~~~~The objective of this paper is a comparison between two fundamentally different approaches to assess risks due to natural hazard impacts on roads. Using the standardized framework from ASTRA (2012) for operational risk assessment for roads and transportation networks, we supplement the well-established deterministic method with a probabilistic framework for risk calculation (Fig. 1). While the former calculates risk with constant or discrete values, ignoring the epistemic uncertainty of the variables, the latter enables the consideration of the potential range of parameter value by using different distributions to characterize the input data uncertainty. Even though the presented methodology in this study focuses on a road segment exposed to a multi-hazard environment on a local-scale, the approach can easily be~~

~~transferred to other risk-oriented purposes.~~



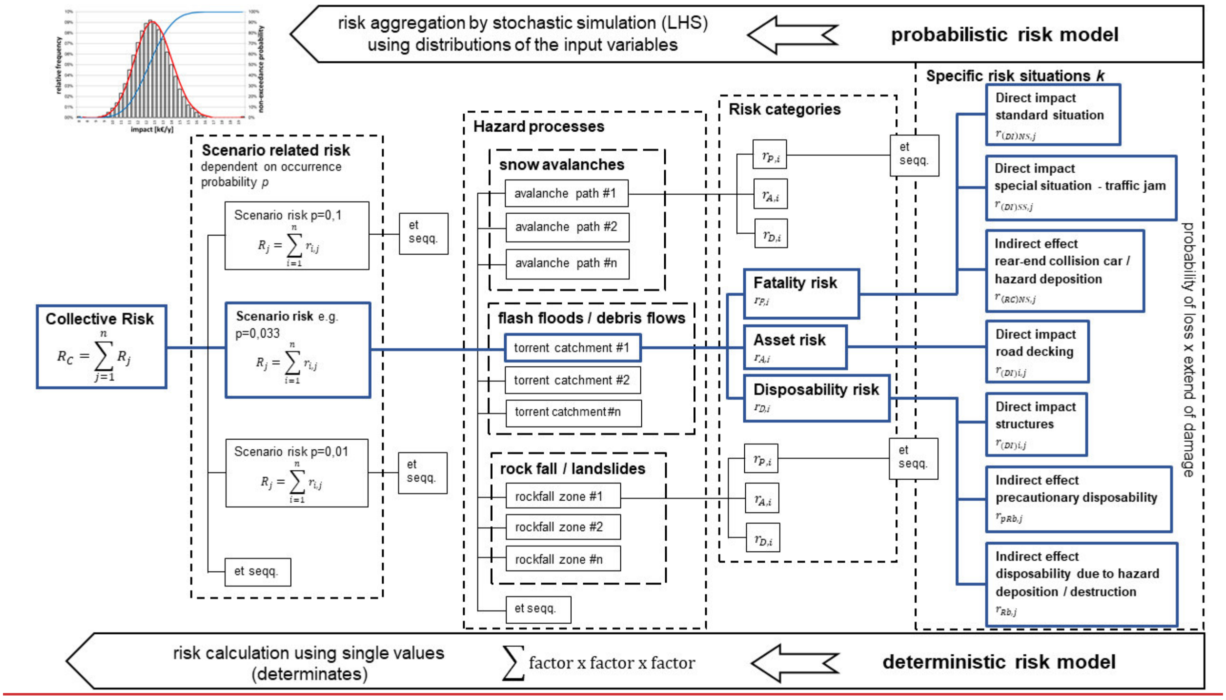


Figure 1. Exemplified ~~F~~flow chart for the risk assessment method following the standard approach (deterministic risk model) from ASTRA (2012) which was supplemented with the probabilistic risk model in present study. In the deterministic approach each risk variable is addressed with single values and the specific risk situations are summed up to risk categories for each hazard process class and scenario (probability of occurrence of the hazard process) and finally to the collective risk, whereas the probabilistic setup uses a probability distributions to characterize each risk variable and further aggregates risk by stochastic simulation to the total risk.

2 Background

2.1 Multi-hazard risk assessment

According to Kappes et al. (2012a), two approaches to multi-hazard risk analysis can be distinguished, a spatially-oriented and a thematically-defined method. While the first aims to include all relevant hazards and associated loss in an area, the latter deals with the influence or interaction of one hazard process on another hazard, frequently addressed as hazards chain or cascading hazards, meaning that the occurrence of one hazard is triggering one or several second-order (successive) hazards. One of the major issues in multi-hazard risk analysis – see Kappes et al. (2012a) for a comprehensive overview – lies in the different process characteristics which lead to challenges for a sound comparison of the resulting risk level among different hazard types due to different reference units. Standardization by a classification scheme for frequency and intensity thresholds of different hazard types resulting in semi-quantitative classes or ranges allows for a comparison among different hazard types, such as shown in Table 2. Therefore, the analysis of risk for transport infrastructure is often focused on an assessment of different hazard types affecting a defined road section rather than on hazard chains or cascades (Schlögl et al., 2019). Following this approach, hazard-specific vulnerability can be assessed either in terms of loss estimates (e.g., Papathoma-Köhle et al., 2011; Fuchs et al., 2019) or in terms of other socioeconomic variables, such as limited access in case of road blockage or interruption (Schlögl et al., 2019). Focusing on the first and neglecting any type of hazard chains, our study demonstrates the application of risk to a specific road section in the Eastern European Alps and shows the sensitivity of the results using deterministic and probabilistic risk approaches.

2.2 Deterministic risk concept

Quantitative risk analyses for natural hazards are regularly based on deterministic approaches, and the temporal and spatial occurrence probability of a hazard process with a given magnitude is multiplied by the expected consequences, the latter defined by values at risk times vulnerability (Varnes, 1984; International Organisation for Standardisation, 2009). A universal definition of risk relates the likelihood of an event with the expected consequences, thus manifests risk as a function of hazard times consequences (UNISDR, 2004; ISO, 2009). Depending on the spatial and temporal scale, values at risk include exposed elements, such as buildings (Fuchs et al., 2015, 2017), infrastructure systems (Guikema et al., 2015) and people at risk (Fuchs et al., 2013). These elements at risk are linked to potential loss using vulnerability functions, indices or indicators (Papathoma-Köhle, 2017), and can be expressed in terms of direct and indirect, as well as tangible and intangible loss (Markantonis et al., 2012; Meyer et al., 2013). While direct loss occurs immediately due to the physical impact of the hazard, indirect loss occurs with a certain time lag after an event (Merz et al., 2004, 2010). Furthermore, the distinction between tangible or intangible loss is depending on whether or not the consequences can be assessed in monetary terms. In this context, vulnerability is defined as the degree of loss given to an element of risk as a result from the occurrence of a natural phenomenon of a given intensity, ranging between 0 (no damage) and 1 (total loss) (UNDRO, 1979; Fell et al., 2008;

Fuchs, 2009). This definition highlights a physical approach to vulnerability within the domain of natural sciences, neglecting any societal dimension of risk. However, the expression of vulnerability due to the impact of a threat on the element at risk considerably differs among hazard types (Papathoma-Köhle et al., 2011).

Using a deterministic approach, the calculation of risk has repeatedly been conceptualised by Eq. (1) (e.g. Fuchs et al. 2007; Oberndorfer et al. 2007; Bründl et al. 2009) and is dependent on a variety of variables all of which being subject to uncertainties (Grêt-Regamey and Straub, 2006).

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

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.

With respect to mountain hazard risk assessment, standardised approaches are available, such as IUGS (1997), Dai et al. (2002), Bell and Glade (2004), and Fell et al. (2008a, b) for landslides, Bründl et al. (2010) for snow avalanches, and Bründl (2009) or ASTRA (2012) for a multi-hazard environment. These approaches, however, usually neglect the inherent uncertainties of involved variables. In particular, they ignore the probability distributions of the variables (Grêt-Regamey and Straub, 2006) by obtaining the results with constant input parameters, which may lead to ~~inconsistencies~~ bias (over- and underestimation dependent on the scale of input variables) in the results. Therefore, loss assessment for natural hazard risk is associated with high uncertainty (Špačková et al., 2014 and Špačková, 2016) and studies quantifying uncertainties of the expected consequences are underrepresented (Grêt-Regamey and Straub, 2006), especially regarding natural hazards impacts on roads (Schlögl et al., 2019). For the assessment of an optimal mitigation strategy for an avalanche-prone road Rheinberger et al. (2009) considers parameter uncertainty by assuming a joint (symmetric) deviation of ±5 % for all input values to construct a confidence interval for the baseline risk. The assessment of uncertainty of natural hazard risk is therefore frequently represented by sensitivity analyses to show the sensitivity through a shift in input values on the results. Thus, the use of confidence intervals allows a discrete calculation of risk with different model setups. In our study, we ~~bridge this gap by quantifying~~ quantify the potential uncertainties within road risk assessment using a stochastic risk assessment approach under consideration of the probability distribution of input data.

2.3 Uncertainties within risk assessment

Since the computation of risk for roads requires a variety of auxiliary calculations, a broad range of input data are used, such as the spatial and temporal probability of occurrence of specific design events. These auxiliary calculations subsequently provide variables necessary for risk computation of the respective system under investigation. Individual contributing variables are often characterized either as ~~the~~ mean value of the potential spectrum from a statistical dataset or, as a consequence of incomplete data, as a single value form expert judgement. Expert information is frequently processed with semi-quantitative probability classes and therefore subjected to considerable uncertainties. Consequently, they serve as rough qualitative appraisals encompassing a high degree of uncertainty.

The use of vulnerability parameters or lethality values as a function of process-specific intensities is often based on incomplete or insufficient statistical data resulting from missing event documentation (Fuchs et al., 2013). As discussed in Kappes et al. (2012a), Papathoma-Köhle et al. (2011, 2017) and Ciurean et al. (2017) with respect to mountain hazards, potential sources of uncertainty in vulnerability assessment are independent of the applied assessment method. The amplitude in data is considerably high in continuous vulnerability curves or functions, but also in discrete (minimum and maximum) vulnerability values referred to as matrices (coefficients), and in indicator-/index-based methods used to calculate the cumulative probability of loss. With regard to ~~Associated with~~ the uncertainty in vulnerability matrices, Ciurean et al. (2017) suggested a fully probabilistic simulation in order to quantify the propagation of errors between the different stages of analysis by substituting the range of minimum-maximum values with a probability distribution for each variable in the model.

Grêt-Regamey and Straub (2006) listed potential sources of uncertainties in risk assessment models and classified uncertainties into aleatory and epistemic uncertainties. The first is considered as inherent to a system associated to the natural variability over space and time (Winter et al., 2018) and the variability of underlying random or stochastic processes (Merz and Thieken, 2005, 2009), which cannot be further reduced by an increase in knowledge, information or data. The latter results from incomplete knowledge and can be reduced with an increase of cognition or better information of the system under investigation (Merz and Thieken, 2004, 2009; Grêt-Regamey and Straub, 2006). Particularly referring to deterministic risk analysis, epistemic uncertainty is associated with a lack of knowledge about quantities of fixed but poorly known values (Merz and Thieken, 2009). Špačková (2016) pointed out the importance of interactions (correlations) between uncertainties which may affect the final results, an issue that was also discussed in the framework of multi-hazard risk assessments (Kappes, 2012a, b). Therefore, uncertainties should be included in the analysis by their upper and lower credible limits or by integrating confidence intervals reflecting the incertitude of input data, for an in-depth discussion see e.g. Apel et al. (2004), Merz and Thieken (2004, 2009), Bründl et al. (2009) and Winter et al. (2018).

2.4 Deterministic vs. probabilistic risk

Deterministic and probabilistic methods for risk analysis differ significantly in approach. Deterministic methods generally use a defined value (point value) for probability and for the impact (consequence) and consider risk by multiplying the probability of occurrence with the potential consequences. The result is an “expected value” of risk. If multiple risks e.g. with varying frequencies are addressed, the total risk is expressed as the simple sum of single risks resulting in an expected annual average loss. However, information about probability or best and/or worst-case scenarios are often excluded. In particular, the following shortcomings of deterministic approaches can be summarized (Tecklenburg 2003), which in turn leads us to a recommendation of probability-based risk approaches:

- A deterministic method gives equal weight to those risks that have a low probability of occurrence and high impact and to those risks that have a high probability of occurrence and low impact by using a simple multiplication of probability and impact, a topic which is also known as risk aversion effect and is controversially discussed in the literature (e.g., Wachinger et al, 2013; Lechowska, 2018).
- By multiplying the two elements of probability and impact, these values are no longer independent. Therefore, this method is not adequate for aggregation of risks where both probability and impact information need to remain available. Due to multiplication, the only information that remains is the mean value.
- The actual impact will definitely deviate from the deterministic value (i.e., the mean).

- Without the Value at Risk (VaR) information, there is no way to determine how reliable the mean value is and how likely it might be exceeded. The VaR is a measure of risk in economics and describes the probability of loss within a time unit, which is expressed as a specified quantile of the loss distribution (Cottin and Döhler, 2013).

In this context, deterministic systems are perfectly predictable, and the state of the parameters to describe the system behaviour are fixed (single) values associated with total determinization following an entirely known rule, whereas probabilistic systems include some degree of uncertainty and the variables/parameters to describe the state of the system are therefore random (Kirchsteiger, 1999). The variables/parameters in probabilistic systems are described with probability distributions due to incomplete knowledge, rather than with a discrete single or point value which is assumed to be totally certain. Probabilistic risk modelling uses stochastic simulation with a defined distribution function to generate random results within the setting of the boundary conditions. The deterministic variable is usually included within the input distribution. In Table 1 the two different methods are compared.

Table 1. Deterministic versus probabilistic method for risk analysis adjusted and compiled from Sander et al. (2015) and Kirchsteiger (1999).

	Deterministic method	**Probabilistic method**
Input	Definition of a single number for consequence as descriptive statements including conservative assumptions expressed by the probability of occurrence multiplied by the impact of the particular hazard.	The probabilistic assessment of risk requires at least one number or – for an entirely probabilistic modelling – a PDF for the probability of occurrence and several values for the impact (e.g., minimum, most likely and maximum) expressed as distribution functions, therefore including uncertainty.
Result	A simple mathematical addition to give the aggregated consequence for all risks (point value calculation). This results in an expected consequence for the aggregated risks but does not adequately represent the bandwidth (range) of the aggregated consequences. The deterministic calculation can be supplemented with upper and lower bounds (different model setups) to show the sensitivity of the input on the results using a sensitivity analysis, which are per se separate deterministic calculations.	Simulation methods e.g. Monte Carlo simulation produce a bandwidth (range) of aggregated natural hazards risks as probability distribution based on thousands of coincidental but realistic scenarios (depiction of realistic risk combinations). The method allows an explicit consideration and treatment of all types of reducible uncertainty.
Qualification	Results (monetary value or fatality per time unit) are displayed as a single sharp number, which, in itself, does not have an associated probability.	Results are displayed using probability distributions, which allow Value at Risk (VaR) interpretation for each value within the bandwidth (range).

~~In contrast to the well-established deterministic approach for mountain hazard risk assessment, probabilistic methods are underrepresented as a standard procedure to cope with the uncertainties of complex safety-relevant surroundings. To overcome this gap,~~In our study we present an probabilistic design for loss calculation in order to compute the potential spectrum of input data with simple distribution functions and further aggregate the intermediate data of exposure situations, hazard- and scenario-related modules to the probability density function (PDF) of the total collective risk R_C by means of stochastic simulation (Fig. 1). Consequently, damage induced by natural hazards impact to road infrastructure as well as to traffic are represented by a range of monetary values as a prognostic distribution of the expected annual average loss instead of an individual amount.

~~Deterministic and probabilistic methods for risk analysis differ significantly in approach. Deterministic methods generally use a defined value (point value) for probability and for the impact (consequence) and consider risk by multiplying the probability of occurrence and potential consequences. The result is an "expected value" of risk. If multiple risks e.g. with varying frequencies are addressed, the total risk is expressed as the simple sum of individual risks resulting in an expected annual average loss. However, information about probability or best and/or worst-case scenarios are often excluded. In particular, the following shortcomings of deterministic approaches can be summarized (Tecklenburg 2003), which in turn leads us to a recommendation of probability-based risk approaches:~~

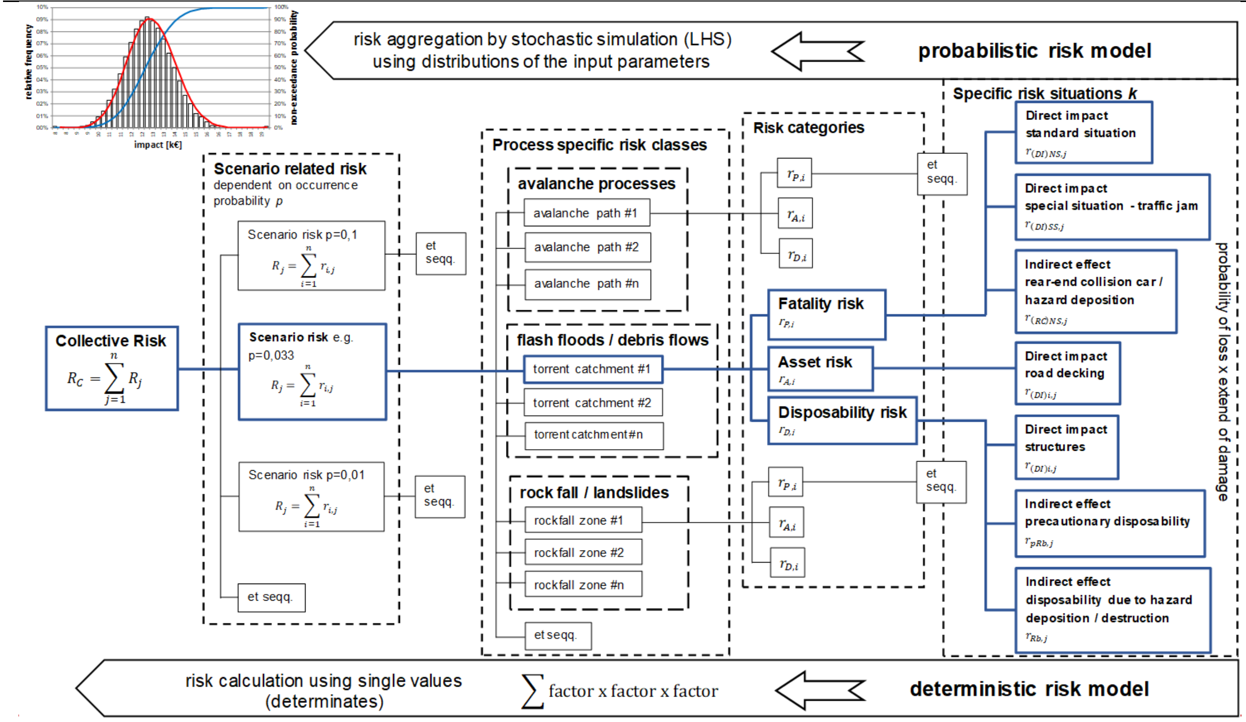
- ~~A deterministic method gives equal weight to those risks that have a low probability of occurrence and high impact and to those risks that have a high probability of occurrence and low impact by using a simple multiplication of probability and impact.~~
- ~~By multiplying the two elements of probability and impact, these values are no longer independent. Therefore, this method is not adequate for aggregation of risks where both probability and impact information need to remain available. Due to multiplication, the only information that remains is the mean value.~~
- ~~The actual impact will definitely deviate from the deterministic value (i.e., the mean).~~
- ~~Without the Value at Risk information, there is no way to determine how reliable the mean value is and how likely it might be exceeded.~~

~~In this context, deterministic systems are perfectly predictable, and the state of the parameters to describe the system behavior are fixed (single) values associated with total determinization following an entirely known rule, whereas probabilistic systems include some degree of uncertainty and the variables/parameters to describe the state of the system are therefore random (Kirchsteiger, 1999). The variables/parameters in probabilistic systems are described with probability distributions due to incomplete knowledge, rather than with a discrete single or point value which is assumed to be totally certain. Probabilistic risk modelling uses stochastic simulation with a defined distribution function to generate random results within the setting of the boundary conditions. The deterministic variable is usually included within the input distribution. In Table 1 the two different methods are compared.~~

~~**Table 1.** Deterministic versus probabilistic method for risk analysis adjusted and compiled from Sander et al. (2015) and Kirchsteiger (1999).~~

	~~**Deterministic method**~~	~~**Probabilistic method**~~
~~Input~~	~~Definition of a single number for consequence as descriptive statements including conservative assumptions expressed by the probability of occurrence multiplied by the impact of the particular hazard.~~	~~The probabilistic assessment of risk requires one number for the probability of occurrence and several values for the impact (e.g., minimum, most likely and maximum) expressed as distribution functions, therefore including uncertainty.~~
~~Result~~	~~A simple mathematical addition to give the aggregated consequence for all risks (point value calculation). This results in an expected consequence for the aggregated risks but does not adequately represent the~~	~~Simulation methods e.g. Monte Carlo simulation produce a bandwidth (range) of aggregated natural hazards risks as probability distribution based on thousands of coincidental but realistic scenarios (depiction of realistic risk combinations). The method~~

	~~bandwidth (range) of the aggregated consequences.~~	~~allows an explicit consideration and treatment of all types of reducible uncertainty.~~
~~Qualification~~	~~Results are displayed as a single sharp number, which, in itself, does not have an associated probability.~~	~~Results are displayed using probability distributions, which allow Value at Risk (VaR) interpretation for each value within the bandwidth (range).~~



~~**Figure 1.** Flow chart for the risk assessment method following the standard approach (deterministic risk model) from ASTRA (2012) which was supplemented with the probabilistic risk model in present study.~~

~~2~~3. Case study

The study area is located in the Eastern European Alps, within the Federal State of Salzburg, Austria (Fig. 2). The case study is a road segment of the federal highway B99 with an overall length of two kilometers ranging from km 52.8 to km 54.8 and is endangered by multiple types of natural hazards. The road segment was chosen to demonstrate the advantages of using probabilistic risk approaches in comparison to traditional deterministic methods. The mountain road under examination is part of a north-south traverse over the main ridge of the Eastern European Alps and is therefore an important regional transit route. Furthermore, the road provides access to the ski resort of Obertauern.

As shown in Fig. 2, the road segment is affected by three avalanche paths, four torrent catchments and one rockfall area. The four torrent catchments have steep alluvial fans on the valley basin. The road segment is located at the base of these fans or the road is slightly notched in the torrential cone and passes the channels either with bridges or with culverts. The rockfall area is situated in the west~~ district ~~ern part of the road segment~~ (Fig. 2)~~. Approximately two third of the study area is affected from rock fall processes either as single blocks or by multiple blocks.

The road is frequently used for individual traffic from both sides of the alpine pass. Hence, a mean daily traffic (MDT) of 3,600 cars is observed. This constant frequency represents the standard situation for the potentially exposed elements at risk. However, especially in the winter months the average daily traffic can considerably increase up to an amount of about 7,000 cars. Thus, the traffic data underlies short-term daily and longer-term seasonal fluctuations with peaks up to the double of the mean value. The importance of dynamic risk computation needed for traffic corridors was also discussed earlier by Zischg et al. (2005) and Fuchs et al. (2013) with respect to the spatial-temporal shifts in elements at risk. Besides of the use as a regional transit route, the road is also a central bypass for one of the main transit routes through the Eastern European Alps. Hence, any closure of this main transit route (A10 Tauern motorway) results in a significant increase of daily traffic frequency up to a total of 19,650 cars. The evaluation of the dataset in terms of the bandwidth of the traffic data is shown in Table A6.

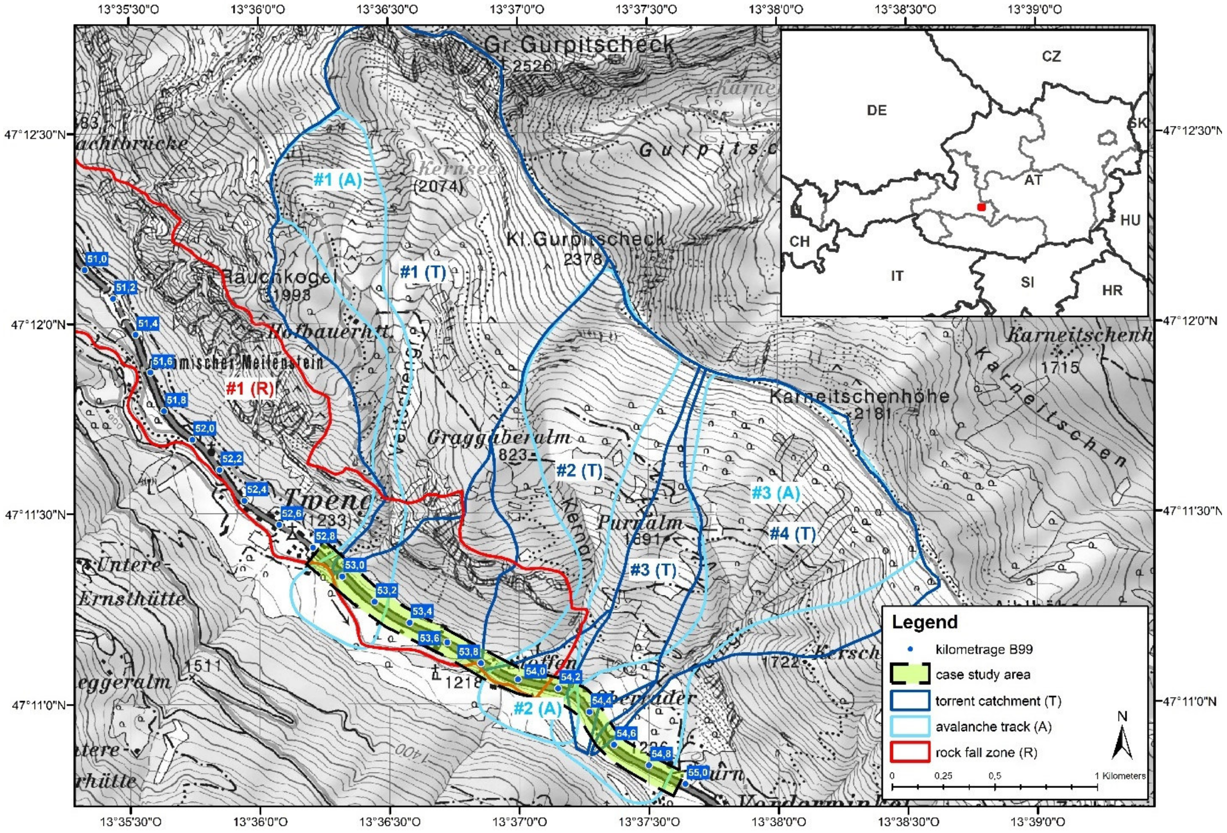


Figure 2. Overview of the case study area and location of the natural hazards along the road segment (Source base map: © BEV 2020 – Federal Office of Metrology and Surveying, Austria, with permission N2020/69708).

~~3~~4. Methods

~~3~~4.1 Hazard analysis

The hazard analysis was ~~conducted in~~part of technical studies undertaken for the road authority of the Federal State of Salzburg (Geoconsult, 2016; Oberndorfer, 2016). The results regarding the spatial impact of the hazard processes on the elements at risk and the corresponding hazard intensities were used for the loss assessment in this research.

The hazard assessment included the steps of hazard disposition analysis to detect potential hazards sources within the perimeter of the road followed by a detailed numerical hazard analysis. Therefore, these analyses considered approaches for hazard-specific impact assessment according to the engineering guidelines of e.g. Bründl (2009), ASTRA (2012) and Bründl et al. (2015) and relevant engineering standards and technical regulations (Austrian Standards Organisation, 2009, 2010, 2017). The physical impact parameters of the hazard processes were calculated using numerical simulation software, such as Flow-2D for flash floods and debris flows (Flow-2D Software, 2017), SamosAT for dense and powder snow avalanches (Sampl, 2007) and Rockyfor3D for rock fall (Dorren, 2012). The hazard analyses were executed without probabilistic calculations;~~,~~ thus, the generated results were integrated as constant input in the risk analysis.

For the multi-hazard purpose three hazard types were evaluated, (1) hydrological hazards (torrential floods, flash floods, debris flows), (2) geological hazards (rock fall, landslides), and (3) snow avalanches (dense and powder snow avalanches). For each hazard type, intensity maps for the affected road segment were computed. The intensity maps specify for a specific hazard scenario the spatial ~~expression~~ extent of a certain physical impact (e.g., pressure, velocity, or inundation depth) during a reference period (Bründl et al., 2009). In order to transfer the physical impact to object-specific vulnerability values for further use in the risk assessment, three process-specific intensity classes were distinguished (Table 2). These intensity classes were based on the underlying technical guidelines (Bründl, 2009; ASTRA, 2012; Bründl et al., 2015) and were slightly adapted to comply with the regulatory framework in Austria (Republik Österreich, 1975, 1976; BMLFUW, 2011). Table 2 represents the intensity classes which correspond to the affiliated object-specific vulnerability and lethality values (mean damage values) in Tables A7 and A8.

Table 2. Process-specific intensity classes with p = pressure, h = height (suffix h_{ws} refers to water and solids), v = velocity, d = depth and E = energy (compiled and adapted from Bründl (2009), ASTRA (2012) and Republik Österreich (1975) in conjunction with Republik Österreich (1976) and BMLFUW (2011). The low intensity class for debris flow has the same intensity indicators than for inundation because it was assumed that low intensity debris flow events have equal characteristics than hydrological processes.

Hazard type	**Low intensity**	**Medium intensity**	**High intensity**
Snow avalanche	$1 < p < 3$ kN/m²	$3 < p < 10$ kN/m²	$p > 10$ kN/m²
Inundation	$h < 0.5$ m or $v \times h < 0.5$ m²/s	$0.5 < h_{ws} < 1.5$ m or $0.5 < v \times h < 1.5$ m²/s	$h_{ws} > 1.5$ m or $v \times h > 1.5$ m²/s
Debris (bed load) deposit	$h_{ws} < 0.5$ m or $v \times h < 0.5$ m²/s	$0.5 < h_s < 0.7$ m or $v < 1$ m/s	$h_s > 0.7$ m and $v > 1.0$ m/s
Erosion	--	$d < 1.5$ m or top edge of the erosion	$d > 1.5$ m or top edge of the erosion
Rockfall	$E < 30$ kJ	$30 < E < 300$ kJ	$E > 300$ kJ

To determine the intensities of individual hazard processes, two different return periods were selected, a 1-in-10-year and a 1-in-30-year event (probability of occurrence $p_{10} = 0.1$ and $p_{30} = 0.033$). ~~As shown in Fig. 2, the road segment is affected by three avalanche paths, four torrent catchments and one rockfall area.~~ All three snow avalanches can either develop as powder snow avalanches or as dense flow avalanches, depending on the meteorological and/or snowpack conditions. Due to the catchment characteristics of the torrents two different indicator processes were assigned for assessing the hazard effect, depending on the two occurrence intervals. Therefore, the occurrence interval served as a proxy for the process type since we assumed ~~. F~~for the frequently occurring events (p = 0.1) the hazard type "flash floods with sediment transport" and for the medium scale recurrence intervals (p = 0.033) debris flow processes. ~~were assumed.~~ ~~The four torrent catchments have steep alluvial fans on the valley basin. The road segment is located at the base of these fans or the road is slightly notched in the torrential cone and passes the channels either with bridges or with culverts. The rockfall area is situated in the west district of the road segment (Fig. 2). Approximately two third of the study area is affected from rock fall processes either as single blocks or by multiple blocks.~~

~~3~~4.2 Standard guideline for risk assessment

The method to calculate road risk for our case study followed the deterministic standard framework of the ASTRA (2012) guideline for operational road risk assessment. The identification of elements at risk regarding their quantity, characteristics and value as well as their temporal and spatial variability was assessed through an exposure analysis. The assessment of the vulnerability of objects (affected road segment, culverts, bridges etc.) and the lethality of persons was carried out by a consequence analysis to characterize the extent of potential losses. The finally resulting collective risk R_C (Eqn. 2) as a sum of all hazard types over all object classes and scenarios – under the assumption that the occurrence of the individual hazards are independent from each other – was expressed in monetary terms per year as a prognostic value. R_C is therefore defined as the expected annual damage caused by certain hazards and is frequently used as a risk indicator (Merz et al., 2009; Špačková et al., 2014). Hence, R_C was calculated based on Eqn. (1) by summing up the partial risk over all scenarios j and objects i (Bründl et al., 2009, Bründl, 2009, ASTRA, 2012, Bründl et al., 2015):

$$R_C = \sum_{j=1}^{n} R_{C,j} \tag{2}$$

Where $R_{C,j}$ = the total collective risk of scenario j and objects i, $R_{C,j} = \sum_{i=1}^{n} r_{i,j}$.

According to the ASTRA (2012) guideline, the collective risk R_C is divided into three main risk groups, (1) risk for persons R_P, (2) property or asset risk R_A, and (3) risk of non-operational availability or disposability R_D.

~~3~~4.2.1 Risk for persons R_P

The risk characterization for persons in terms of the direct impact of a natural hazard on cars was distinguished in a standard situation for flowing traffic and a situation during a traffic jam, which was seen as specific situation leading to a significant increase of potentially endangered persons. Additionally, another specific case was also included representing the rear-end collision either on stagnant cars or on the process depositions on the road in case of the standard situation. The probability for a rear-end collision depends on the characteristics of the road and is influenced by a factor of e.g. the visual range, the winding and steepness of the road, the velocity, and traffic density (ASTRA, 2012). Furthermore, an additional specific scenario was explicitly considered in the case of the road closure of the main transit route (A10 Tauern motorway) due to the resulting temporal peak of the mean daily traffic.

The statistical mean daily traffic (MDT) was used as mean quantity of persons N_p travelling along the road (Table A7).

In order to compute R_P, the expected annual losses of ~~a~~ persons ~~i~~ traveling along the road segment under a defined hazard scenario j was calculated as a combination of the specific damage potential or potential damage extent of a persons ~~i~~ and the damage probability of the exposure situation k for persons using the road under investigation. The potential losses for persons were monetized by the cost for a statistical human life as published by the Austrian Federal Ministry of Transportation, Innovation and Technology (BMVIT, 2014). The published average national expenses of road accidents include materially and immaterially costs (body injury, property damage and overhead expenses) of road accidents and are based on statistical evaluations of the national database as well as on the willingness to pay approach for human suffering. The monetized costs for a statistical human life equal 3 M€. Thus, road risk for persons was calculated with three road-specific exposure situations k (Bründl et al., 2009):

1. Direct impact of the hazard event – standard situation (Eqn. 1A; Table A1)
2. Direct impact of the hazard event – specific situation due to traffic jam (Eqn. 2A; Table A2)
3. Indirect effect – ~~Rear~~rear-end collision (Eqn. 3A; Table A3)

The risk variables to assess R_P are stated in Table A6 for the exposure situations and in Table A7 in the Appendix.

~~3~~4.2.2 Property risk R_A

The property risk due to the direct impact~~s~~ of the hazard process on physical assets of the road infrastructure was calculated for each object i and scenario j using Eqn. (4A) with Table A4 under consideration of risk variables in Table A8. The damage probability was assumed to be equal to the frequency of the scenario j.

With respect to the potential direct tangible losses within the study area, the physical assets including e.g. the road decking of the street segment, culverts and bridges were expressed by the building costs of the assets calculated from a reference price per unit (Table A8). The physical assets of affected cars were not addressed as this damage type is not included in the standard guideline due to the assumption of an obligatory insurance coverage. The monetized costs refer to replacement costs and reconstruction costs, respectively, instead of depreciated values, which is strongly recommended in risk analysis by Merz et al. (2010) due to the fact that replacement cost systematically overestimates the damage. Since there is a limitation of reliable or even available data on replacement costs, the usage of reconstruction costs is a pragmatic procedure to calculate damage.

~~3~~4.2.3 Risk due to non-operational availability R_D

The risk due to non-operational availability can be generally separated into economic losses due to (1) road closure after a hazard event or (2) as a result of precautionary measures for road blockage. The former addresses the mandatory reconditioning of the road and interruption time is depending on the severity of the damage. For our case study, only the precautionary non-operational availability was calculated with Eqn. (5A), Table A5 and variables in Table A9 because the village of Obertauern can be accessed from both directions of the mountain pass road. Therefore, a general accessibility of the village was supposed because it was assumed that events only lead to a road closure on one site of the pass. Potential costs resulting from time delays for necessary detours or e.g. from an increase of environmental or other stresses were neglected. The maximum intensity of the process served as a proxy for the duration of the road closure.

The direct intangible costs for non-operational availability of the road were approximated from statistical data accounting for the business interruption and the loss of profits of the tourism sector in the village of Obertauern due to road closure (see Table A9). The village of Obertauern is a major regional tourism hot spot and therefore the predominant income revenues are based on tourism, thus other business divisions ~~have been~~were neglected. Regarding the precautionary expected losses only snow avalanches were included, due to the obligatory legal implementation of a monitoring of a reginal avalanche commission. Thus, a reliable procedure for a road closure could be assumed.

~~3~~4.3 Risk computation

For purpose of computing road risk, the risk Equations 1A to 5A from the standard guideline (ASTRA, 2012), stated in the Appendix in conjunction with Tables A1 to A5, were used without further modification both for the deterministic and for the probabilistic calculation. Hence, the probabilistic setup is based on the same equations as the standard approach, but the variables were addressed with probability distributions instead of single values. In a first step, the deterministic result was computed as a base value for comparison with the results (probability density functions PDFs) of the two diverging probabilistic setups. In a second step, a probabilistic model was integrated into the same calculation setup to consider the band width of the risk-contributing variables. Using this probabilistic model, the individual risk variables were addressed with two separate probability distributions. The flow chart in Fig. 1 illustrates the risk assessment method and distinguishes between the deterministic and the probabilistic risk model. The diagram exemplarily demonstrates the calculation steps for both model setups. Whereas only the single value of the input data was processed within the standard (deterministic) setup, the probabilistic risk model utilized the bandwidth of each variable denoted in Tables A6 to A9 in the Appendix. These values were either defined from statistical data, expert judgement or from existing literature. The range represents the ~~expected~~ assumed potential scatter of the variables including a minimum (lower bound *l*), an expected or most likely value (*m*) and a maximum value (upper bund *u*). The deterministic setup was calculated with the expected value, which corresponds in most cases to the recommended input value of the guideline. The choice of the variable range in Tables A6 to A9 in the Appendix is case study specific and cannot be transferred to other studies without careful validation.

~~3~~4.3.1 Probabilistic framework

Within the probabilistic risk modelling setup, the contributing variables for computing the prognostic annual loss were calculated in a stochastic way using their potential range. The probabilistic risk calculation was conducted with the software package RIAAT – Risk Administration and Analysis Tool (RiskConsult, 2016). The probabilistic setup comprised two different and independent calculation runs each with two different distribution functions to characterize the uncertainty of the input variables. Hence, each variable was modelled using either (1) a triangular or three-point distribution (TPD) or (2) a beta-PERT distribution (BPD) within the probabilistic model, which generated two independent probabilistic setups and results. The discrete risk calculation with two different approaches of probability distributions facilitated a comparison of the applicability and the sensitivity of the simple distribution functions on the results. The expected annual monetary losses induced by the three hazard types were aggregated and further compacted to the probability density function (PDF) of the total risk caused by multi-hazard impact. Finally, the two different PDFs from the stochastic risk assessment were compared with the result from the deterministic method to show the potential dynamics in the results.

1. Triangular distribution (TPD)

The triangular distribution derives its statistical properties from the geometry: it is defined by three parameters *l* for lower bound, *m* for most likely value (the mode) and *u* for upper bound. Whereas lower and upper bounds define on both edges the limited bandwidth, the most likely value indicates that values in the middle are more probable than the boundary values, and also allows for the representation of skewness. The TPD is a popular distribution in the risk analysis field (Cottin and Döhler, 2013) for example to reproduce expert estimates. Especially if little or no information about the actual distribution of the parameter or only an estimate of the additional variables to fit the theoretical distribution is feasible, a best possible approximation can be achieved using the TPD. If there is no representative empirical data available as a basis for risk prediction, complex analytical (theoretical) distributions, which are harder to model and communicate, may not represent the reality better than a simple triangular distribution (Sander, 2012).

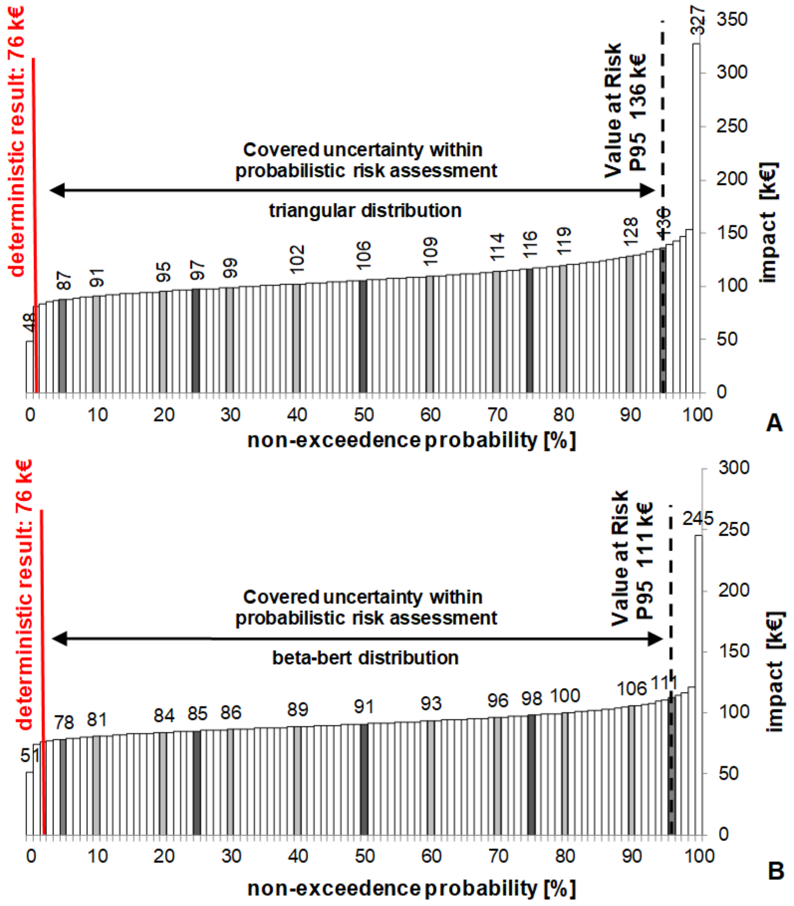
2. Beta-PERT distribution (BPD)

The beta-PERT distribution (Program Evaluation and Review Technique) is a simplification of the Beta distribution with the advantage of an easier modelling and application (Sander, 2012). It requires the same three parameters as a triangular distribution: *l* for lower bound, *m* for most likely value (mode) and *u* for upper bound. In contrast to the two parametric normal distribution N(μ,σ) – μ for average and σ for standard deviation – the beta-PERT distribution is limited on the edges and it allows for modelling asymmetric situations. ~~In reality, r~~Risk parameters commonly have a natural boundary, for example vulnerability factors ranging from 0 (no loss) to 1 (total loss). Therefore, estimating min/max values instead of standard deviation is more realistic or feasible as there is in most cases no data available to express the mean variation. Moreover, BPD allows for smoother shapes, making it suitable to model a distribution that is actually an aggregation of several other distributions.

For a given number of risks, each with a probability of occurrence and an individual probability distribution, the potential number of combinations (scenarios) escalates nonlinear. Especially if dependencies or correlations between different risks are included and/or numerous partial risks are aggregated to an overall risk the application of analytical methods have computational restrictions. Stochastic simulations are better suited to work on such complex models (Tecklenburg, 2003). Therefore, the aggregation of the distributions were calculated by means of Latin Hyp~~b~~ercube sampling (LHS) which is a comparable stochastic simulation technique to Monte-Carlo simulation (MCS) with the advantage of a faster data processing, a better fitting on the theoretical input distribution and a more efficiently calculation as fewer iterations are needed to get equally good results (Sander, 2012). LHS consistently produces values for the distribution’s statistics that are nearer to the theoretical values of the input distribution than MCS. These advantages are possible because the real random numbers used to select samples for the MCS tend to have local clusters, which are only averaged out for a very large number of draws. Addressing this issue using LHS can immediately improve the quality of the result by splitting the probability distribution into *n* intervals of equal probability, where *n* is the number of iterations that are to be performed on the model. In the present study, 1,000,000 iterations where performed for every single simulation to get consistent results.

~~4~~5. Results and discussion

In Table 3 the results for each risk group (R_P, R_A, R_D) as well as for the total multi-hazard risk R_C calculated with the standard deterministic risk approach are shown and compared to those obtained by the two probabilistic setups using two different probability distributions (TPD and BPD). The results associated with the two distribution functions are displayed as median value of the PDF to show their deviation to the outcome of the standard approach. Based on our case study, the road risk over all hazards types and scenarios (multi-hazard risk) with the deterministic approach results in 76.0 k€/y. The results with the probabilistic approach referring to the median of the PDFs amounts to a monetary risk of 105.6 k€/y (TPD) and 90.9 k€/y (BPD), respectively. Compared to the standard approach the median of the PDFs equals an increase of 38 % (BPD) and 19 % (TPD), depending on the choice of probability distribution to model the uncertainties of the input variables. Focusing on the 95 % percentile (P95) of the results – non-exceedance probability of 95 %, shown in Fig. 3 – an increase of 79 % (TPD) and 46 % (BDP) to the deterministic result can be observed. Fig. 3 illustrates, based on the Lorenz curves for the two distributions (TPD and BPD), the scale of deviation of the total multi-hazard risk R_C within the probabilistic risk modelling and compared to the standard outcome. The graphs show the potential uncertainties of the risk computation, which can be covered by a suitable choice of a Value at Risk (VaR) level. For example, with a benchmark of the 95 % quantile (P95), 95 % of the potential uncertainties within the risk calculation can be covered by using a probabilistic risk assessment approach. However, a suitable VaR level is depended on the general safety requirement of the system as well as on the degree of uncertainty of the input variables.


deterministic result: 76 k€
Covered uncertainty within probabilistic risk assessment
triangular distribution
Value at Risk P95 136 k€
48
87
91
95
97
99
102
106
109
114
116
119
128
136
327
0
50
100
150
200
250
300
350
impact [k€]
0
10
20
30
40
50
60
70
80
90
100
non-exceedence probability [%]
A
deterministic result: 76 k€
Covered uncertainty within probabilistic risk assessment
beta-bert distribution
Value at Risk P95 111 k€
51
78
81
84
85
86
89
91
93
96
98
100
106
111
245
0
50
100
150
200
250
300
impact [k€]
0
10
20
30
40
50
60
70
80
90
100
non-exceedence probability [%]
B

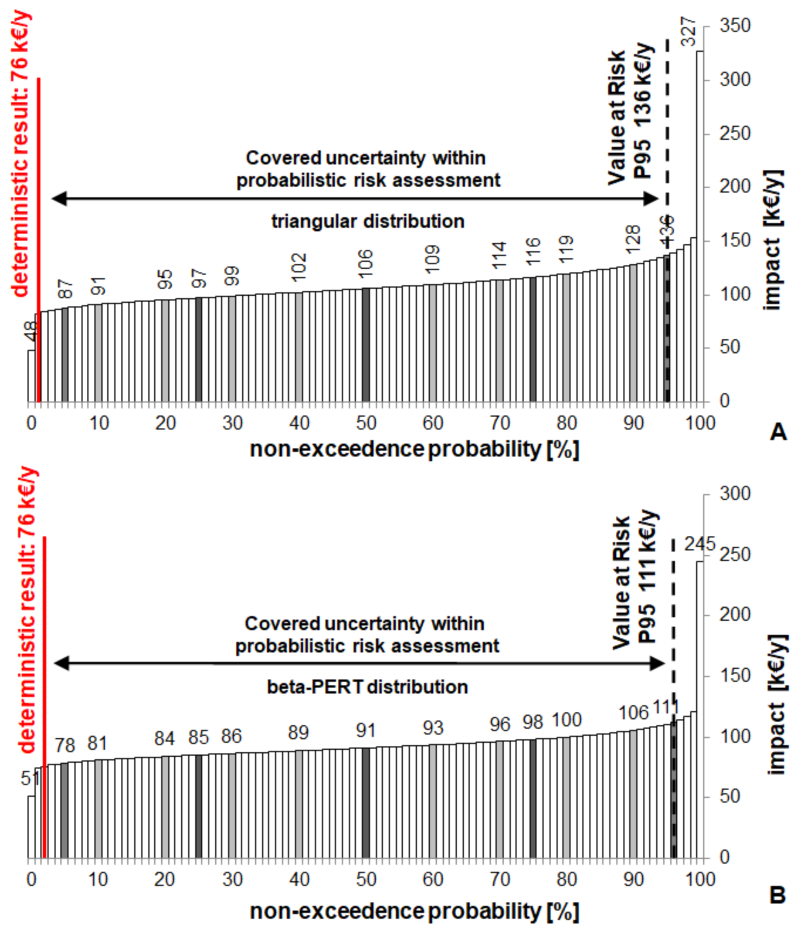


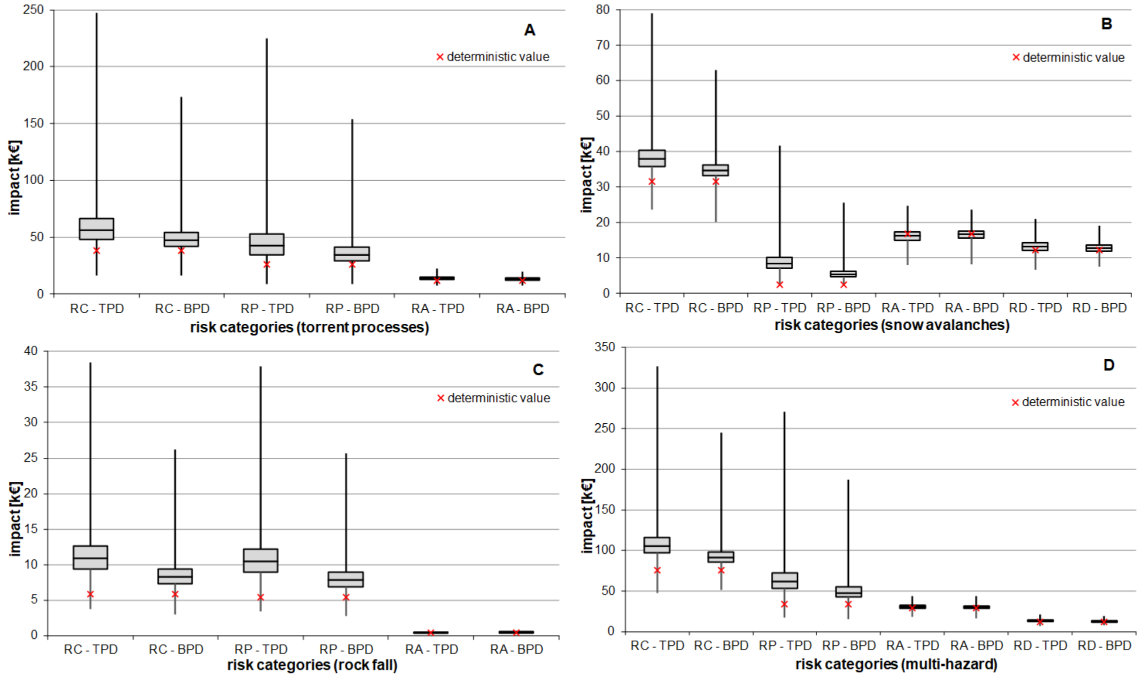
Figure 3. Lorenz curves for (A) triangular distribution and (B) beta-PERT distribution showing the scale of deviation of the total multi-hazard risk R_C within the probabilistic risk modelling and compared to the deterministic result in k€/y.

Geological hazards (rockfall) contribute with a fraction of 7.8 % to the total risk (or, in absolute numbers, 5.9 k€, see Table 3) based on the deterministic model, which can be attributed to the relatively small importance in comparison to the other hazard types in the study area. Hydrological hazards pose the highest risk (50.5 %, or, in absolute numbers, 38.4 k€/y) previous to avalanche hazards (41.7 %, or, in absolute numbers, 31.7 k€/y). Overall, R_P (44.9 %; 34.1 k€/y) has the highest share on the total multi-hazard risk narrowly followed by R_A (38.9 %; 29.6 k€/y), both associated to direct damage. The hydrological hazards (predominantly debris flow processes) with a portion of 76.5 % or 26.1 k€/y have a disproportionate high share on R_P due to the high-intensity hazard impact. Similarly, the semi-empirical lethality factors shown in Table A7 have high values ($\lambda_D = 0.8$) just like the impact of rock fall on cars with a probability of death of $\lambda_R = 1.0$. Thus, these event types yield in high monetary losses in contrast to snow avalanches with a lethality factor for high intensity of $\lambda_A = 0.2$. By modelling the hazard-specific lethality with probability functions a wider scatter can be achieved but the effect still remains due to the heavy weight around the most likely value *m*. The indirect losses related to R_D with a fraction of 16.3 %, or, in absolute numbers 12.4 k€/y ~~has~~ have a minor portion because this risk group is only relevant for snow avalanches.

Table 3. Comparison of the deterministic versus probabilistic results for the three risk categories depending on the three hazard types and the total collective risk with R_P = risk for persons, R_A asset risk, R_D = disposability risk and R_C = total collective risk with absolute values in k€/y in the first row and as percentage in the second row. For the probabilistic data, the median value of the triangular △ and the beta-PERT ⌒ distribution functions are displayed. Note that, risk-based aggregated losses do not equal the sum of the sub-components because probabilistic metrics such as P50 are not additive. Thus, the computational sum as well as the percentage are slightly different.

Risk category		**R_P**			**R_A**			**R_D**			**R_C**		
Hazard type	**Unit**	**Det.**	△	⌒	**Det.**	△	⌒	**Det.**	△	⌒	**Det.**	△	⌒
Geological hazards	k€/y	5.4	10.5	7.8	0.47	0.43	0.44	0	0	0	5.9	10.9	8.3
	%	15.8	17.0	16.3	1.6	1.4	1.5	0	0	0	7.8	10.3	9.1
Hydrological hazards	k€/y	26.1	42.3	34.5	12.3	13.9	13.1	0	0	0	38.4	56.2	47.6
	%	76.5	68.3	71.9	41.6	45.6	43.5	0	0	0	50.5	53.2	52.4
Avalanche hazards	k€/y	2.6	8.4	5.3	16.8	16.2	16.6	12.4	13.1	12.7	31.7	37.9	34.7
	%	7.6	13.6	11.0	56.8	53.1	55.1	100	100	100	41.7	35.9	38.2
Total	k€/y	**34.1**	**61.9**	**48.0**	**29.6**	**30.5**	**30.1**	**12.4**	**13.1**	**12.7**	**76.0**	**105.6**	**90.9**
	%	**44.9**	**58.6**	**52.8**	**38.9**	**28.9**	**33.1**	**16.3**	**12.4**	**14.0**	**100**	**100**	**100**

The results related to our case study (Table 3 and Fig. 4) show that due to the shape and the mathematical definition of the distribution the TPD leads to the highest variation in the monetary losses. The boxplots in Fig. 4 display the results from the probabilistic simulation for the three risk categories (R_P, R_A, R_D) and for the total hazard-specific risk (R_C) relating to the three hazard types (Figs. 3 A – C) and for the total multi-hazard collective risk (Fig. 4 D) in respect of the measures of the central tendency of the PDF. The boxplot diagrams are thereby plotted against the deterministic value to show its position. The wide range of the distribution in R_C is markedly caused by R_P, which exhibits a broad bandwidth and a right-skewed distribution. Hence, unlike to R_A and R_D, the physical injuries expressed as the economic losses of persons (R_P) are responsible for the highest divergence to the standard approach and show a considerable scatter. The main causes for the striking deviations can be associated to the relatively high monetary value of persons which was modelled as discrete point value in combination with the fluctuations of the MDT and the variations of the hazard specific lethality. The monetized costs for a statistical human life equal 3 M€ (Table A7) and is based on a statistical survey of the economic expenses for a road accident in Austria (BMVIT, 2014). Although we ascribe this value to a high degree of uncertainty the valuation of the expenses for a statistical human life was not attributed to a probability distribution due to the case study-specific fixed governmental requirements in Austria. The discussion of a monetarily evaluation of a human life is still ongoing across scientific disciplines using different economic approaches (e.g. Hood, 2017). Furthermore, the lethality factors also correspond to the high variation of R_P which are seen as very sensitive parameters. Therefore, we encourage further research on hazard-specific lethality functions for road risk management either based on comprehensive empirical datasets or on representative hazard impact modelling. Due to the strong effect of R_P on R_C the results have to be carefully interpreted as they are sensitive to the input variables. Therefore, the values on our case study especially the cost for human life cannot be directly transferred to other application without a detailed validation and verification of national regulations.



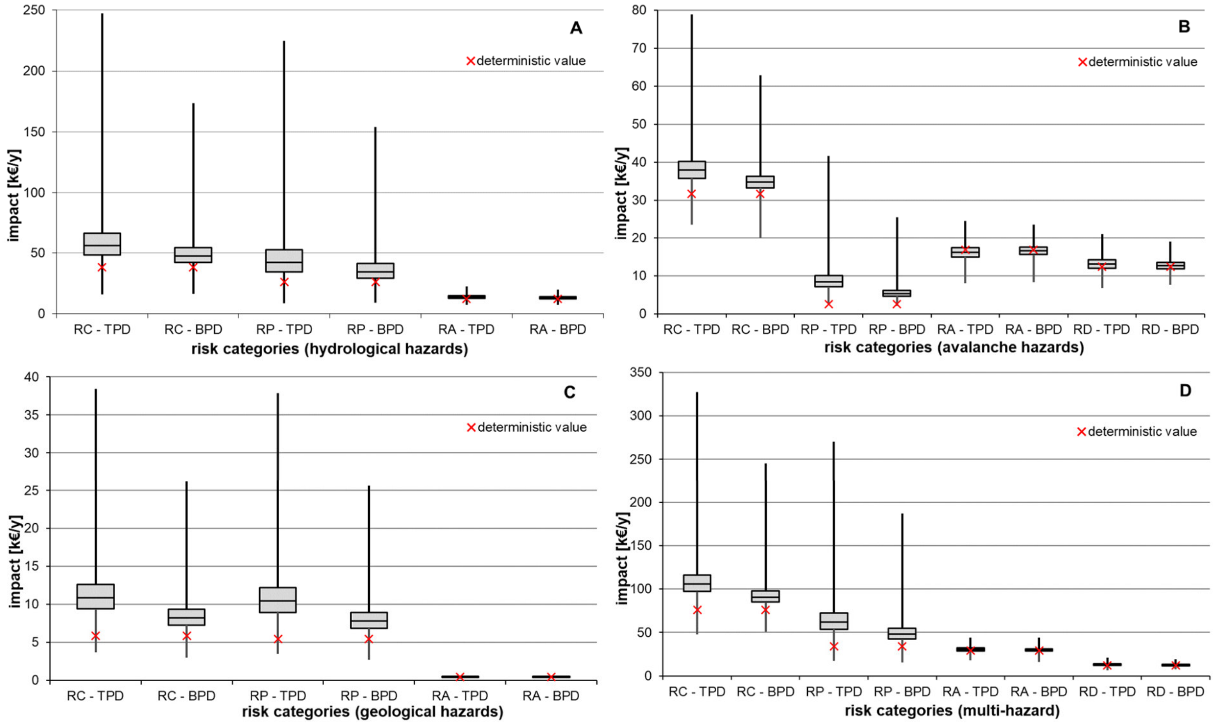
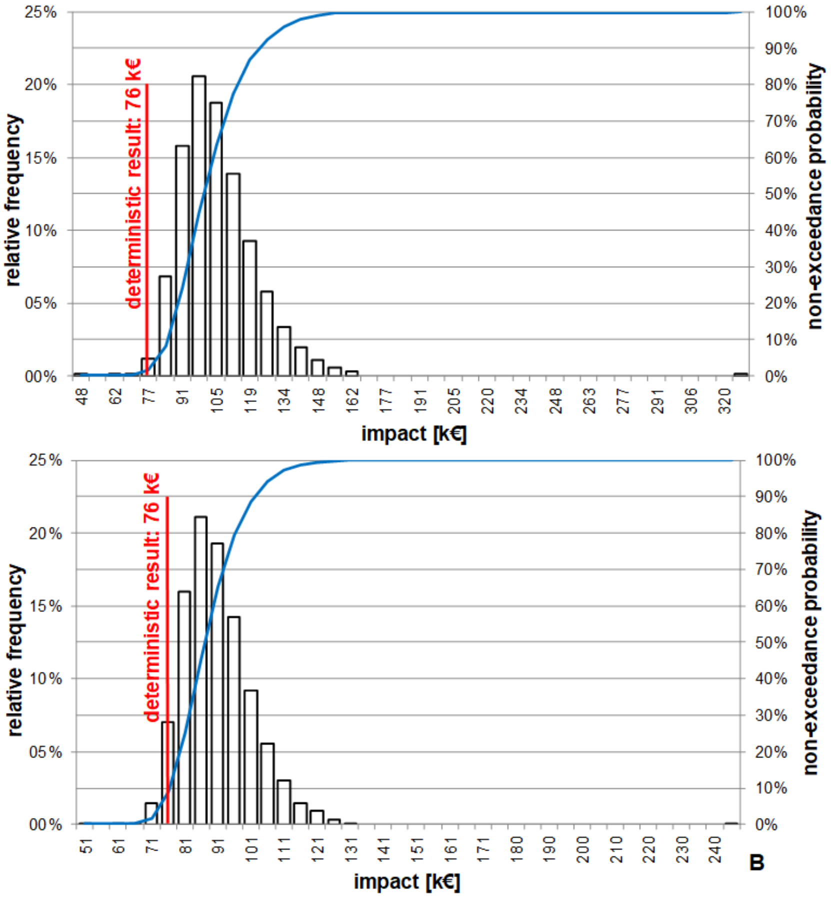


Figure 4. Probabilistic results for the three risk categories per hazard type (A = torrent processes, B = snow avalanches, C = rockfall) and for the total collective risk (D) based on the two distribution functions triangular or three-point distribution (TPD) and the beta-PERT distribution (BPD) with R_P = risk for persons, R_A asset risk, R_D = disposability risk and R_C = total collective risk in k€/year.

Apart from R_P where the deterministic result is located below or near the 5 % percentile of both PDFs, R_A and R_D are mostly within the interquartile range between the 25 % quartile and the median compared to the standard approach (Fig. 4). In this context, R_A for snow avalanche exceeds the median and is situated between the median and the 75 % quartile. The effect can be traced back to the left-skewed distribution of the vulnerability factor $v_{B,\mathrm{A}}$ for medium avalanche hazard intensities regarding the object class structures (bridges and culverts) in Table A8. In general, due to the shape and the mathematical characteristics of the distribution, the BPD leads to a stronger compaction around the median than the TPD which can be well explained by the properties of the BPD which has, in comparison to the TPD, a larger weight around the most likely value m.


relative frequency
non-exceedance probability
deterministic result: 76 k€
impact [k€]
25%
20%
15%
10%
05%
00%
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
48
62
77
91
105
119
134
148
162
177
191
205
220
234
248
263
277
291
306
320
relative frequency
non-exceedance probability
deterministic result: 76 k€
impact [k€]
25 %
20 %
15 %
10 %
05 %
00 %
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
51
61
71
81
91
101
111
121
131
141
151
161
171
180
190
200
210
220
230
240
B

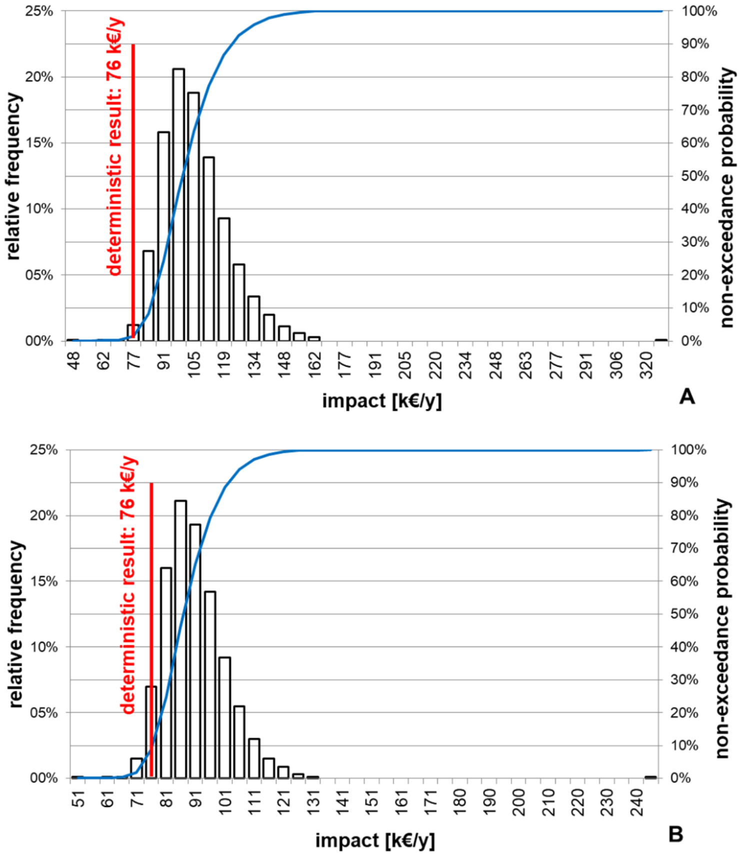


Figure 5. Probability density function (PDF) and cumulative distribution function (CDF) for (A) triangular distribution, (B) beta-PERT distribution in k€/y.

In Fig. 5, the PDF and the cumulative distribution function (CDF) are shown for R_C with the two probabilistic model results and the deterministic result. In both cases (TPD and BPD), the deterministic result is situated at the lower edge of the PDF near or under the 5 % percentile. Thus, the deterministic result of our case study covers approximately less than 5 % of the potential band-with of the probability distribution. The TPD has a wide range, whereas the BPD is considerably flattened on the boundary of the amplitude. The results of the two distributions have in common that they are allocated right ~~-~~skewed. In contrast to the location of the median, the deterministic result is on the far-left side of both distribution and is exceeded of more than 95 % of the potential outcome.

~~5~~ 6 Conclusion

The results based on our case study provide evidence that the monetary risk calculated with a standard deterministic method following the conventional guidelines is lower than applying a probabilistic 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 mathematical product of the frequency of occurrence and the potential consequences with single values and, in a narrower sense, the multiplication of the partial risk factors in the second part of the risk equation may lead to a bias in the risk magnitude because the multiplication of the ancillary calculations generates a theoretical value ignoring the full scope of the total risk.

The far left position of the deterministic value within the PDF of the probabilistic result in our study can be traced back to fact that the multiplication of two positive symmetrical distributions results in a right-skewed distribution, because the product of the small numbers at the lower ends of the bandwidths results in much smaller numbers than the product of the high numbers at the upper ends of the bandwidths. When right-skewed distributions are used as input and aggregated, the effect of skewness shifts the deterministic value (represented by the most likely value) to the right side of the resulting distribution. Even if conservative risk values are used in a deterministic setup, a potential scatter (upper and lower bounds) remains, which leads within a probabilistic calculation through aggregation of the partial risk elements and sub-results to a right-skewed distribution according to the skewness of input variables. Since risk values of our study are in most cases asymmetric with primarily positive skews, the deterministic result migrates during aggregation to the left side of the PDF in Fig. 5. The deterministic risk value is usually expressed either as a theoretical mean value or as most likely value neglecting the potential distribution functions of the input data. Thus, the compression of the input values to a single deterministic risk value with total determination prevents an actual prognosis of reliability that would have been achieved by specifying bandwidths (Sander, 2012). Furthermore, the simple summation of the scenario related and the object-based risk to receive the cumulative risk level instead of using probabilistic risk aggregation leads to an underestimation of the final risk. Hence, the full spectrum of risk cannot be represented with deterministic risk assessment, which may further lead to biased decisions on risk mitigation.

The Value at Risk (VaR) approach by considering a reliable percentile of the non-exceedance probability e.g. P95 as shown in Fig. 3 – depending on the desired covering of the risk potential form society, authorities or organizations – might be an appropriate concept to tackle this challenge. In this context, a higher VaR value implies a higher safety level for the system under investigation. The final results of risk assessments are subject to uncertainties mainly due to insufficient data basis of input variables, which can be addressed using a PDF to represent uncertainties involved. For further decisions on the realization of mitigation measures a high VaR value such as P95 covers these uncertainties with a defined shortfall probability and thus supports decision makers with more information of road risk. In turn, as a further practical improvement this benchmark can be compared to the same grade of safety for the costs of mitigation measures since cost assessments for defence structures are also subject to considerable uncertainties. Thus, an optimal risk-based design of defence structures might encompass a balance between the same VaR level both of a probabilistic risk and a probabilistic cost assessment utilizing a cost benefit analysis (CBA).

However, within a probabilistic approach the scale of deviation is dependent on the choice of distribution for modelling the bandwidth of the variables and the results are sensitive to the defined spectrum of input information stated in Tables A6 - A9. These variables are case study specific and cannot be directly transferred to other road risk assessments without careful validation. However, probabilistic risk assessment (PRA) enables a transparent representation of potential losses due to the explicit consideration of the entire potential bandwidth of the variables contributing to risk. Since comparable results can be achieved based on predefined values (Bründl et al., 2009), we still recommend the consideration of the deterministic value as a comparative value to the probabilistic method.

Road risk assessment is usually afflicted to data scarcity; thus, risk operators and practitioners are often dependent on expert appraisals, which are subject to uncertainties. In order to improve data quality, upper and lower values and the expected value can be easily estimated for fitting a simple distribution of the input variables. Even though empirical values such as statistical data are available, a certain degree of uncertainty remains. Therefore, simple distribution functions such as TPD or BPD can adjust the shape of the distribution more conveniently than complex probability distributions, since the required additional parameters to adjust a complex distribution are simple not available. Hence, for a prognostic prediction, risk modelling with complex distributions in contrast to simple techniques cannot be justified if there is a lack of empirical data.

A limitation of our study is that the performance of the probabilistic approach cannot be verified and validated with empirical data, but the results show that the explicit inclusion of epistemic uncertainty leads to a bias in risk magnitude. The probabilistic approach allows quantification of uncertainty, and thus enables decision makers to better assess the quality and validity of the results from road risk assessments. This can facilitate the improvement of road-safety guidelines (for example by implementing a VaR concept), and thus is of particular importance for authorities responsible for operational road-safety, for design engineers and for policy makers due to a general increase of information for optimal decision-making under budget constraints. Furthermore, the paper addresses the second part of the risk concept in terms of the consequence analysis. The results of the hazard analysis serve thereby as a constant input using the physical modelling of the hazard processes without the consideration of probabilistic methods. Thus, the probability of occurrence of the hazard processes was mathematically processed as point value within the probabilistic design since the hazard analyses (with deterministic design events to assess the hazard intensities as a function of the return interval) was part of prior technical studies. Further considerations of a probabilistic modelling of the frequency of the events were outside of the study design and might be addresses in subsequent studies. Therefore, we expect a considerable source of epistemic uncertainty within the hazard analysis which emphasises the necessity for an additional inclusion of probabilistic based hazard analyses in a holistic multi-hazard risk environment. Even though the presented methodology in this study focuses on a road segment exposed to a multi-hazard environment on a local-scale, the approach can easily be transferred to other risk-oriented purposes.

Acknowledgments: This work was supported by the Federal State government of Salzburg, Austria, especially from the Geological Service under supervision of L. Fegerl and G. Valentin. The geological hazard analysis was conducted by Geoconsult ZT-GmbH by A. Schober on behalf of the Federal State government of Salzburg which provided the hazard data for the risk analysis. The authors were supported by BOKU Vienna Open Access Publishing Fund.

Competing interests: Sven Fuchs is member of the Editorial Board of Natural Hazards and Earth System Sciences.

Author contribution: SO initiated the research, was responsible for data collection, literature research, preparation of the manuscript, visualization of the results and performed the risk simulations with additional contribution by PS. PS contributed to additional information on probabilistic risk calculation. SF compiled the background on risk assessment and helped to shape the research, analysis and the manuscript. All authors discussed the results and contributed to the final manuscript.

Data availability: All risk related data are publicly available (see references throughout the paper as well as in the Appendix).

Appendix

Risk equations according to ASTRA (2012) guideline:

A. Risk for persons R_P

1. Direct impact of the hazard event – standard situation

$$r_{(DI)NS,j} = p_j \times (1 - p_{Rb}) \times (1 - p_{RbE}) \times p_N \times N_P \times \lambda \times p_{So,j} \times f_L \tag{1A}$$

Table A1. Risk variables and their derivation for the calculation of R_P – direct impact standard situation. (*)The reduction factor considers that not all hazard areas get simultaneously released by the same triggering event. (#)The number of hazard areas for the three hazard types was calculated as discrete values based on field surveys according to the release probability as a function of the event frequency (avalanches n_{A10} = 6, n_{A30} = 7; torrent processes n_{T10} = 7, n_{T30} = 8; rockfall p_{RbE} = 0 not relevant). (x)The length of the affected street segment is a discrete (single) value according to the results of the hazard analyses.

Variable	Description	Derivation
$r_{(DI)NS,j}$	risk of ~~a~~ persons ~~i~~ in scenario *j* (normal situation)	
p_j	probability of occurrence of an event (frequency of a scenario *j*)	$p_j = f_j - f_{j+1};\ f_j = \frac{1}{T_j}$ p_j = probability of occurrence of scenario *j* f_j = frequency of occurrence T_j= return period of scenario *j*
p_{Rb}	probability of precautionary road blockage	
p_{RbE}	probability of a road blockage due to an event (road closure due to a previous event of the same hazard type along the road)	$p_{RbE} = \alpha \times \left(1 - \frac{1}{n_H}\right)$ α = reduction factor(*) n_H= number of hazard areas with the same hazard process and triggering mechanism(#)
p_N	probability of the standard (normal) situation	$p_N = 1 - p_C$
p_C	probability of a traffic jam (congestion)	$p_C = \left(\frac{n}{365}\right) \times \left(\frac{D}{24}\right)$ n = number of traffic jams per year D = average duration of a traffic jam [h]
N_p	number of affected persons	$N_P = N_V \times \beta$ $N_{VN} = \frac{MDT}{v \times 24000} \times l$ = number of vehicles in the standard situation $N_{V\cancel{S}J} = \frac{(\rho_{max} \times l)}{1000}$ = number of vehicles in case of a traffic jam MDT = mean daily traffic v = signalized velocity for cars [km/h] l = length of the street segment [m](x) ρ_{max} = maximum traffic density per lane and kilometer in case of a traffic jam β = mean degree of passengers
λ	lethality factor	Hazard-process and intensity related variable ($\lambda_D, \lambda_{F,} \lambda_R, \lambda_A$ in table A6)
$p_{So,j}$~~$p_{So,j}$~~	spatial occurrence probability of the	for rockfall processes $p_{So,j} = ET \times \frac{d}{w_{HD}}$

	process in the scenario j as proportion of the mean width or area of the process domain in scenario j to the maximum width or area of the potential hazard domain	ET = event type d = mean diameter of the block [m] w_{HD} = width or amplitude of the hazard domain in scenario j
f_L	factor to differentiate the affected lane	0,5 = one lane affected 1 = whole road (both lanes) affected

2. Direct impact of the hazard event – special situation due to traffic jam

$$r_{(DI)SS,j} = p_j \times (1 - p_{Rb}) \times (1 - p_{RbE}) \times p_C \times N_P \times \lambda \times p_{So,j} \times f_L \tag{2A}$$

Table A2. Risk of ~~a~~ persons ~~i~~ in scenario j for the calculation of R_P – direct impact traffic jam. The calculation of the variables is according to Table A1.

Variable	Description
$r_{(DI)SS,j}$	risk of ~~a~~ persons ~~i~~ in scenario j in case of a traffic jam (special situation)

3. Indirect effect – Rear-end collision

$$r_{(RC)NS,j} = p_j \times (1 - p_{Rb}) \times (1 - p_{RbE}) \times p_{Rc} \times f_L \times (1 - p_C) \times N_P \times \lambda_{\mathrm{Rc}} \tag{3A}$$

Table A3. Risk variables and their description for the calculation of R_P – rear-end collision. The calculation of the residual variables is according to Table A1. $^{(*)}$A rear-end collision is only valid in case of a standard situation (no traffic jam). The scenario is not relevant for low intensity hazard events with deposition heights < 0,15 m.

Variable	Description
$r_{(RC)NS,j}$	risk of ~~a~~ persons ~~i~~ in scenario j for a rear-end collision in the normal situation$^{(*)}$
p_{Rc}	probability of rear-end collision
λ_{Rc}	probability of fatality in the case of a rear-end collision

B. Property risk R_A

$$r_{(DI)i,j} = p_j \times l \times A_i \times v_{i,j} \times p_{So,j} \times f_L \tag{4A}$$

Table A4. Risk variables and their description for the calculation of R_A – direct impact. The calculation of the residual variables is according to Table A1.

Variable	Description
$r_{(DI)i,j}$	risk of object i in scenario j in terms of a direct impact of the hazard
A_i	asset value of object i
$v_{i,j}$	hazard-specific vulnerability of object i in scenario j (in table A7)
l	length of the affected road segment

C. Risk due to non-operational availability R_D

$$r_{Rb,j} = \left(p_{ji} \times f_{Rb} \times \frac{1}{n_H}\right) \times D_{Rb} \times C_{Rb} \qquad (5A)$$

Table A5. Risk variables and their description for the calculation of R_D. The calculation of the residual variables is according to Table A1.

Variable	Description
$r_{Rb,j}$	risk of a roadblock in scenario j
f_{Rb}	frequency of road blockage
D_{Rb}	duration of road blockage depended on the hazard type
C_{Rb}	costs of a road blockage
n_H	number of hazard areas which are responsible for road closure

Risk variables:

A. Probability of loss – exposure

Table A6. Band width (credible intervals with *l* - lower bound, *m* - most likely value and *u* - upper bound) of the variables within the probabilistic risk analysis for calculating exposure situations. Units: h for hours, n for numbers, y for years. $^{(*)}$Event type 1\|5\|10 equates to single stone \| multiple stones \| small scale rockslide.

Vari-able	Description	Specific-ation	Unit	*l* - lower bound	*m* - most likely value	*u* - upper bound	Source
p_{Rb}	probability of a roadblock	not probable	-	0			m: ASTRA (2012); l, u: Estimates considering ASTRA class limits
		sparse probable		0.05	0.1	0.5	
		probable		0.1	0.5	0.9	
		most likely		0.5	0.9	0.95	
α	reduction factor for p_{RbE}	--	-	0.5	0.75	1	m: ASTRA (2012); l, u: Expert judgements
n_{B99}	number of traffic jams per year	--	n/y	0	1	2	l, m, u: Expert judgements icw. surveyor of highways (Federal State of Salzburg)
D	duration of a traffic jam	--	h	0.083	0.5	2.0	l, m, u: Expert judgements icw. surveyor of highways (Federal State of Salzburg)
f_{A10}	frequency of occurrence special situation A10	--	n/y	5	22	30	l, m, u: Statistical evaluation traffic jam database ASFINAG for the year 2015 (min., mean, max. value)

D_{A10}	duration of a special situation A10	--	h	0.5	2.65	5.0	l, m, u: Statistical evaluation traffic jam database ASFINAG for the year 2015 (min., mean, max. value)
n_{SS}	number of traffic jams in case of a special situation A10	--	n	0	4	11	l, m, u: Statistical evaluation traffic jam database ASFINAG for the year 2015 traffic jam events > 0.5h
D_{A10}	duration of a traffic jam special situation A10	--	h	0.083	1	2	l, m, u: Statistical evaluation traffic jam database ASFINAG for the year 2015
p_{Rc}	Probability of a rear-end collision	improbable	-	0	0.05	0.15	m: ASTRA (2012); l, u: Estimates considering ASTRA class limits
		medium probable		0.05	0.15	0.25	
		frequent		0.15	0.25	0.35	
ET	event type of rock fall$^{(*)}$	--	-	1	5	5	ASTRA (2012) icw. geological expert judgement

D. Degree of damage – Risk for persons R_P

Table A7. Band width (credible intervals *l* - lower bound, *m* - most likely value and *u* - upper bound) of the variables within the probabilistic risk analysis for calculating R_P. Units: h for hours, n for numbers. $^{(*)}$The monetary value of person was used as single (point) value as this value is recommended from the Austrian government.

Vari-able	**Description**	**Specific-ation**	**Unit**	***l* - lower bound**	***m* - most likely value**	***u* - upper bound**	**Source**
λ_{Rc}	probability of fatality in the case of a rear-end collision	--	-	0	0.0066	0.05	m: ASTRA (2012); l, u: Expert judgements icw. surveyor of highways (Federal State of Salzburg)
λ_D	lethality for debris flow	low intensity	-	0			m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0	0.5005	0.7995	
		strong intensity		0.5005	0.7995	1	
λ_F	lethality for dynamic flooding	low intensity	-	0			m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0	0.0025	0.108	
		strong intensity		0.025	0.108	0.20	
λ_R	lethality for rock fall	low intensity	-	0	0.1	0.8	m: ASTRA (2012) and BAFU (2013) l, u: Estimates considering class limits
		medium intensity		0.1	0.8	1	

		strong intensity		0.8	1	1	
λ_A	lethality for avalanche	low intensity	-	0	0.00025	0.1	m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0.00025	0.1	0.2	
		strong intensity		0.1	0.2	1	
MDT_{B99}	Average daily traffic B99	--	n	3.000	3.600	7.000	l, m, u: Traffic counting for the year 2016 (min., mean, max. value) (Federal State of Salzburg)
MDT_{A10}	average daily traffic A10	--	n	10.000	19.638	62.000	l, m, u: Permanent automatic traffic counting ASFINAG for the year 2016 (min., mean, max. value)
v	signalized velocity for cars	free land zone	km/h	80	100	120	m: signalized travel speed; l, u: Expert judgements icw. surveyor of highway (Federal State of Salzburg)
		municipality zone	km/h	45	50	60	
		acceleration / deceleration	km/h	70	80	110	
ρ_{max}	maximum traffic density per lane and kilometer in case of a traffic jam	--	n	120	140	145	m: ASTRA (2012); l, u: Expert judgements icw. surveyor of highway (Federal State of Salzburg)
β	mean degree of passengers	--	n	1	1.76	5	m: ASTRA (2012); l, u: Estimates considering one person (driver) and 5 persons in a car.
C_P	value (cost) of a person	--	€	3,016,194$^{(*)}$			BMVIT (2014) for the period 2014-2016

E. Extent of damage – Risk for material assets R_A

Table A8. Band width (credible intervals *l* - lower bound, *m* - most likely value and *u* - upper bound) of the variables within the probabilistic risk analysis for calculating R_A. $^{(*)}$Base value according to the Federal State of Salzburg: l = - 20 %, u = + 10 % (right-skewed distribution).

Variable	Description	Specification	Unit	*l* - lower bound	*m* - most likely value	*u* - upper bound	Source
A_R	asset value – construction costs road	--	€/m	800	850	1,000	l, m, u: Statistical data from Federal State of Salzburg (min., mean, max. value)

A_B	asset value – construction costs bridges (span with 8-10m)	--	€/m²	1,350	2,200	2,400	l, m, u: Statistical data from Federal State of Salzburg (min., mean, max. value)
A_C	asset value – construction costs pipe culverts DN 500-1200	--	k€	52	65	$71.5^{(*)}$	m: Statistical data from Federal State of Salzburg l = - 20 %; u = + 10 % (right-skewed distribution)
$v_{R,F}$	vulnerability road dynamic flooding	low intensity	-	0	0.05	0.1	m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0.05	0.1	0.45	
		strong intensity		0.1	0.45	0.80	
$v_{B,F}$	vulnerability structures (bridges) dynamic	low intensity	-	0	0.025	0.05	m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0.025	0.05	0.65	
		strong intensity		0.05	0.65	1	
$v_{R,D}$	vulnerability road debris flow	low intensity	-	0	0.05	0.35	m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0.05	0.35	0.65	
		strong intensity		0.35	0.65	1	
$v_{B,D}$	vulnerability structures (bridges, culvert) debris flow	low intensity	-	0	0.025	0.25	m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0.025	0.25	0.95	
		strong intensity		0.25	0.95	1	
$v_{R,A}$	vulnerability road avalanche	low intensity	-	0	0.005	0.1	m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0.005	0.1	0.2	
		strong intensity		0.1	0.2	0.30	
$v_{B,A}$	vulnerability structures (bridges, culvert) avalanche	low intensity	-	0	0.005	0.7	m: ASTRA (2012) and BAFU (2013); l. u: Estimates considering class limits
		medium intensity		0.005	0.7	1	
		strong intensity		0.7	1	1	
$v_{R,R}$	vulnerability road rock fall	low intensity	-	0	0.1	0.5	m: ASTRA (2012) and BAFU (2013) l, u: Estimates considering class limits
		medium intensity		0.1	0.5	1	
		strong intensity		0.5	1	1	

$v_{B,R}$	vulnerability structures (bridges, culvert) rock fall	low intensity	-	0	0.1	0.5	m: ASTRA (2012) and BAFU (2013) l, u: Estimates considering class limits
		medium intensity		0.1	0.5	1	
		strong intensity		0.5	1	1	

B. Degree of damage – Risk for operational availability R_D

Table A9. Band width (credible intervals *l* - lower bound, *m* - most likely value and *u* - upper bound) of the variables within the probabilistic risk analysis for calculating R_D. Units: d for days, n for numbers, y for years.

Vari-able	Description	Specific-ation	Unit	*l* - lower bound	*m* - most likely value	*u* - upper bound	Source
f_{Rb}	frequency of road blockage	--	n/y	1	2	4	l, m, u: ASTRA (2012) icw. expert judgements (local avalanche commission)
$D_{Rb,A10}$	duration of a precautionary roadblock for avalanche with return interval T_{10}	--	d	0.33	1	2	l, m, u: ASTRA (2012) icw. expert judgements (local avalanche commission)
$D_{Rb,A30}$	duration of a precautionary roadblock for avalanches with return interval T_{30}	--	d	1	2	3	l, m, u: ASTRA (2012) icw. expert judgements (local avalanche commission)
$C_{Rb,W}$	~~expanses~~ expenses of a roadblock during winter season	--	M€	1.245	1.557	1.868	m: BMNT (2015) CBA with statistical data of guest-night per hotel category (local tourism agency, 2015) l, u: Range of fluctuation +/- 20 %

References

Apel, H., Thieken, A. H., Merz, B., Blöschl, G.: Flood risk assessment and associated uncertainty, Nat. Hazards and Earth Syst. Sci., 4, 295–308, https://doi.org/10.5194/nhess-4-295-2004, 2004.

Austrian Standards International: Protection works for torrent control – Terms and their definitions as well as classification, ONR 24800:2009 02 15, Vienna, 2009.

Austrian Standards International: Permanent technical avalanche protection – Terms, definition, static and dynamic load assumptions, ONR 24805:2010 06 01, Vienna, 2010.

Austrian Standards International: Technical protection against rockfall – Terms and definitions, effects of actions, design, monitoring and maintenance, ONR 24810:2017 02 15, Vienna, 2010.

ASTRA: Naturgefahren auf Nationalstraßen: Risikokonzept, Methodik für eine risikobasierende Beurteilung, Prävention und Bewältigung von gravitativen Naturgefahren auf Nationalstraßen V2.10, Bundesamt für Straßen ASTRA, Bern, 2012.

Bell, R., Glade, T.: Quantitative risk analysis for landslides – Examples from Bíldudalur, NW-Iceland, Nat. Hazards and Earth Syst. Sci., 4, 117-131, https://doi.org/10.5194/nhess-4-117-2004, 2004.

Benn, J. L.: Landlide events on the West Coast, South Island, 1867-2002, New Zealand Geographer, 61, 3-13, https://doi.org/10.1111/j.1745-7939.2005.00001.x, 2005.

BMLFUW: Richtlinie für Gefahrenzonenplanung, 2011.

BMNT: Richtlinien für die Wirtschaftlichkeitsuntersuchung und Priorisierung von Maßnahmen der Wildbach- und Lawinenverbauung (Kosten-Nutzen-Untersuchung), Vienna, available at: https://www.bmnt.gv.at/forst/wildbach-lawinenverbauung/richtliniensammlung/Richtlinien.html, (last access: 01 June 2016), 2015.

BMVIT: Durchschnittliche Unfallkosten Preisstand 2011, Bundesministerium für Verkehr, Innovation und Technologie BMVIT, Vienna, available at: https://www.bmvit.gv.at/verkehr/strasse/sicherheit/strassenverkehrsunfaelle/ukr2012.html. (last access: 01 June 2016), 2014.

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

Bründl, M., Romang, H. E., Bischof, N., Rheinberger, C. M.: The risk concept and its application in natural hazard risk management in Switzerland, Nat. Hazards Earth Syst. Sci., 9, 801–813, https://doi.org/10.5194/nhess-9-801-2009, 2009.

Bründl, M., Bartelt, P., Schweizer, J., Keiler, M., Glade, T.: Review and future challenges in snow avalanche risk analysis, In: Alcántara-Ayala, I., Goudie, A. S. (Eds.), Geomorphological Hazards and Disaster Prevention, Cambridge University Press 2010, pp 49-61, 2010.

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

Bundesamt für Umwelt BAFU (2013): Objektparameterliste EconoMe 2.2, Bern, 2013.

Bunce, C., Cruden, D., Morgenstern, N.: Assessment of the hazard from rock fall on a highway, Canadian Geotechnical Journal, 34, 344-356, https://doi.org/10.1139/t97-009, 1997.

Ciurean, R. L., Hussin, H., van Westen, C. J., Jaboyedoff, M., Nicolet, P., Chen, L., Frigerio, S., Glade, T.: Multi-scale debris flow vulnerability assessment and direct loss estimation of buildings in the Eastern Italian Alps, Nat. Hazards, 85, 929-957, https://doi.org/10.1007/s11069-016-2612-6, 2017.

Cottin, C., Döhler, S.: Risikoanalyse. Modellierung, Beurteilung und Management von Risiken mit Praxisbeispielen, Studienbücher Wirtschaftsmathematik, 2. Auflage, Springer Spektrum, Wiesbaden, https://doi.org.10.1007/978-3-658-00830-7, 2013.

Dai, E.C., Lee, C.F., Ngai, Y.Y.: Landslide risk assessment and management: an overview, Eng. Geol., 64, 65-87, https://doi.org/10.1016/S0013-7952(01)00093-X, 2002.

Dorren, L. K. A.: Rockyfor3D (V5.1) Transparent description of the complete 3D rockfall model, ecorisQ Paper, https://www.ecorisq.com, 2012.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.: Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning, Eng. Geol., 102 (3-4), 85-98, https://doi.org/10.1016/j.enggeo.2008.03.022, 2008a.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.: Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning – Commentary, Eng. Geol., 102 (3-4), 99-111, https://doi.org/10.1016/j.enggeo.2008.03.014, 2008b.

Ferlisi, S., Cascini, L., Corominas, J., Matano, F.: Rockfall risk assessment to persons travelling in vehicles along a road: the case study of the Amalfi coastal road (southern Italy), Nat. Hazards, 62, 691-721, https://doi.org/10.1111/nzg.12170, 2012.

Flow-2D Software: Flow-2D Reference Manual, Nutrioso, 2017.

Fuchs, S., Heiss, K., Hübl, J.: 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/nhess-7-495-2007, 2007.

Fuchs, S.: Susceptibility versus resilience to mountain hazards in Austria – paradigms of vulnerability revisited, Nat. Hazards and Earth Syst. Sci., 9, 337-352, https://doi.org/10.5194/nhess-9-337-2009, 2009.

Fuchs, S., Keiler, M., Sokratov, S., Shnyparkov, A.: Spatiotemporal dynamics: the need for an innovative approach in mountain hazard risk management, Nat. Hazards, 68, 1217-1241, https://doi.org/10.1007/s11069-012-0508-7, 2013.

Fuchs, S., Keiler, M., Zischg, A.: A spatiotemporal multi hazard exposure assessment based on property data, Nat. Hazards and Earth Syst. Sci., 15, 2127-2142, https:/doi.org/ 10.5194/nhess-15-2127-2015, 2015.

Fuchs, S., Röthlisberger, V., Thaler, T., Zischg, A., and Keiler, M.: Natural hazard management from a coevolutionary perspective: Exposure and policy response in the European Alps, Annals of the American Association of Geographers, 107, 382-392, https://doi.org/10.1080/24694452.2016.1235494, 2017.

Fuchs, S., Keiler, M., Ortlepp, R., Schinke, R., Papathoma-Köhle, M.: Recent advances in vulnerability assessment for the built environment exposed to torrential hazards: Challenges and the way forward, J. Hydrol., 575, 587-595, https://doi.org/10.1016/j.jhydrol.2019.05.067, 2019.

Geoconsult ZT GmbH: Gefahrenanalyse B99, Technischer Bericht Sturzprozesse, Salzburg, 2016.

Grêt-Regamey, A., Straub, D.: Spatially explicit avalanche risk assessment linking Bayesian networks to a GIS, Nat. Hazards Earth Syst. Sci., 6, 911–926, https://doi.org/10.5194/nhess-6-911-2006, 2006.

Guikema, S., McLay, L., Lambert, J. H.: Infrastructure Systems, Risk Analysis, and Resilience - Research Gaps and Opportunities, Risk Anal., 35 (4), 560-561, https://doi.org/10.1111/risa.12416, 2015.

Hendrikx, J., Owens, I.: Modified avalanche risk equations to account for waiting traffic on avalanche prone roads, Cold Reg. Sci. and Technol., 51, 214-218, https://doi.org/10.1016/j.coldregions.2007.04.011, 2008.

Hood K.: The science of value: Economic expertise and the valuation of human life in US federal regulatory agencies, Soc. Stud. Sci., 47 (4), 441-465. https://doi.org/10.1177/0306312717693465, 2017.

Hungr, O., Beckie, R.: Assessment of the hazard from rock fall on a highway: Discussion, Canadian Geotechnical Journal, 35, 409, https://doi.org/10.1139/t98-002, 1998.

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

IUGS Committee on Risk Assessment: Quantitative risk assessment for slopes and landslides – The state of the art, In: Cruden, E.M., Fell, R. (Eds.), Proceedings of the International Workshop of Landslide Risk Assessment, Honolulu, pp 3-12, 1997.

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T.: Challenges of analyzing multi-hazard risk: a review, Nat. Hazards, 64, 1925-1958, https://doi.org/10.1007/s11069-012-0294-2, 2012a.

Kappes, M.S., Gruber, K., Frigerio, S., Bell, R., Keiler, M., Glade, T.: The MultiRISK platform: The technical concept and application of a regional-scale multihazard exposure analysis tool, Geomorphology, 151-152, 139-155, https://doi.org/10.1016/j.geomorph.2012.01.024, 2012b.

Kirchsteiger, C.: On the use of probabilistic and deterministic methods in risk analysis, Journal of Loss Prevention in the Process Industries, 12, 399–419, https://doi.org/10.1016/S0950-4230(99)00012-1, 1999.

Kristensen, K., Harbitz, C., Harbitz, A.: Road traffic and avalanches - methods for risk evaluation and risk management, Surveys in Geophysics, 24, 603-616, https://doi.org/10.1023/B:GEOP.0000006085.10702.cf, 2003.

Lechowska, E.: What determines flood risk perception? A review of factors of flood risk perception and relations between its basic elements Natural Hazards, 94, 1341-1366, https://doi.org/10.1007/s11069-018-3480-z, 2018 .

Margreth, S., Stoffel, L., Wilhelm, C.: Winter opening of high alpine pass roads - analysis and case studies from the Swiss Alps, Cold Reg. Sci. and Technol., 37, 467-482, https://doi.org/10.1016/S0165-232X(03)00085-5, 2003.

Markantonis, V., Meyer, V., Schwarze, R.: Valuating the intangible effects of natural hazards – review and analysis of the costing methods, Nat. Hazards Earth Syst. Sci., 12, 1633–1640, https://doi.org/ 10.5194/nhess-12-1633-2012, 2012.

Merz, B., Kreibich, H., Thieken, A. H., Schmidke, R.: Estimation uncertainty of direct monetary flood damage to buildings, Nat. Hazards Earth Syst. Sci., 4, 153–163, https://doi.org/10.5194/nhess-4-153-2004, 2004.

Merz, B., Elmer, F., Thieken, A. H.: Significance of "high probability/low damage" versus "low probability/high damage" flood events, Nat. Hazards Earth Syst. Sci., 9, 1033–1046, https://doi.org/10.5194/nhess-9-1033-2009, 2009.

Merz, B., Thieken, A. H.: Flood risk curves and associated uncertainty bounds, Nat. Hazards, 51, 437–458, https://doi.org/10.1007/s11069-009-9452-6, 2009.

Merz, B., Thieken, A. H.: Separating natural and epistemic uncertainty in flood frequency analysis, Journal of Hydrology, 309, 114–132, https://doi.org/10.1016/j.jhydrol.2004.11.015, 2005.

Merz, B., Kreibich, H., Schwarze, R., Thieken, A. H.: Assessment of economic flood damage, Nat. Hazards Earth Syst. Sci., 10, 1697–1724, https://doi.org/10.5194/nhess-10-1697-2010, 2010.

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J. C. J. M., Bouwer, L. M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A. A., Viavattene, C.: Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps, Nat. Hazards Earth Syst. Sci., 13, 1351-1373, https://doi.org/ 10.5194/nhess-13-1351-2013, 2013.

Michoud, C., Derron, M., Horton, P.: Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps, Nat. Hazards and Earth Syst. Sci., 12, 615-629, https://doi.org/10.5194/nhess-12-615-2012, 2012.

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

Oberndorfer, S.: Technischer Bericht – Gefahrenanalyse Wildbach- & Lawinengefahren B99 Katschberg Straße, Radstadt – Obertauern – Mauterndorf, km 24,70 – km 62,60, Leogang, 2016.

Rheinberger, C.M., Bründl, M., Rhyner, J.: Dealing with the white death: Avalanche risk management for traffic routes, Risk Anal., 29 (1), 76-94, https://doi.org/10.1111/j.1539-6924.2008.01127.x, 2009.

Republik Österreich: Forstgesetz 1975, BGBl 440/1975, Republik Österreich, Vienna, 1975.

Republik Österreich: Verordnung des Bundesministeriums für Land- und Forstwirtschaft vom 30. Juli1976 über die Gefahrenzonenpläne, BGBl 436/1975, Republik Österreich, Vienna, 1976.

Roberds, W.: Estimating temporal and spatial variability and vulnerability, In: Hungr, O., Fell, R., Couture, R. and Eberhardt, E., (Eds.), Landslide risk management, Taylor and Francis Group, London, pp 129-157, 2005.

Schaerer, P.: The avalanche-hazard index, Annals of Glaciology, 13, 241-247, 1989.

Papathoma-Köhle, M., Kappes, M., Keiler, M., Glade, T.: Physical vulnerability assessment for alpine hazards: state of the art and future needs, Nat. Hazards, 58, 645-680, https://doi.org/ 10.1007/s11069-010-9632-4, 2011.

Papathoma-Köhle, M., Gems, B., Sturm, M., Fuchs, S.: Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flow, Earth-Sci. Rev., 171, 272-288, https://doi.org/10.1016/j.earscirev.2017.06.007, 2017.

RiskConsult GmbH: RIAAT Risk Administration and Analysis Tools, Manual, Version 28-F01, Innsbruck, 2015.

Sander, P.: Probabilistische Risiko-Analyse für Bauprojekte. Entwicklung eines branchenorientierten softwaregestützten Risiko-Analyse-Systems, University of Innsbruck, ISBN 978-3-902811-75-2, 2012.

Sander, P., Reilly, J.J. & Moergeli, A.: Quantitative Risk Analysis – Fallacy of the Single Number, ITA World Tunnel Congress, 2015, Dubrovnik, 2015.

Sampl, P.: SamosAT – Beschreibung der Modelltheorie und Numerik, AVL List GmbH, Graz, 2007.

Schaub, Y., Bründl, M: Zur Sensitivität der Risikoberechnung und Maßnahmenbewertung von Naturgefahren, Schweizerische Zeitschrift für ~~das~~ Forstwesen, 161(2), 27-35.

Schlögl, M., Richter, G., Avian, M., Thaler, T., Heiss, G., Lenz, G., Fuchs, S.: On the nexus between landslide susceptibility and transport infrastructure – an agent-based approach, Nat. Hazards and Earth Syst. Sci., 19 (1), 201-219, https://doi.org/10.5194/nhess-19-201-2019, 2019.

Straub, D., Grêt-Regamey, A.: A Bayesian probabilistic framework for avalanche modelling based on observation, Cold Regions Science and Technology, 46, 192–203, https://doi.org/10.1007/978-3-319-09054-2_90, 2006.

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.

Špačková, O.: RAT Risk Analysis Tool. Risk assessment and cost benefit analysis of risk mitigation strategies – Methodology, Engineering Risk Analysis Group, Technical University of Munich, 2016.

Tecklenburg, T.: Risikomanagement bei der Akquisition von Großprojekten in der Bauwirtschaft, Dissertation, TU Braunschweig, Schüling Verlag, Münster, 2003.

UNDRO: Natural disasters and vulnerability analysis, Department of Humanitarian Affairs/United Nations Disaster Relief Office, Geneva, 1979.

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

Unterrader, S., Almond, P., Fuchs, S.: Rockfall in the Port Hills of Christchurch: Seismic and non-seismic fatality risk on roads. New Zealand Geographer, 74 (1), 3-14, https://doi.org/10.1111/nzg.12170, 2018.

Varnes, D.: Landslide hazard zonation: a review of principles and practice. UNESCO, Paris, 1984.

Wachinger, G., Renn, O., Begg, C., and Kuhlicke, C.: The risk perception paradox—implications for governance and communication of natural hazards, Risk Anal., 33, 1049-1065, https://doi.org/10.1111/j.1539-6924.2012.01942.x, 2013.

Wastl, M., Stötter, J., Kleindienst, H.: Avalanche risk assessment for mountain roads: a case study from Iceland, Nat. Hazards, 56, 465-480, https://doi.org/10.1007/s11069-010-9703-6, 2011.

Winter, B., Schneeberger, K., Huttenlau, M., Stötter, J.: Sources of uncertainty in a probabilistic flood risk model, Nat. Hazards, 91, 431–446, https://doi.org/10.1007/s11069-017-3135-5, 2018.

Zischg, A., Fuchs, S., Keiler, M., Meissl, G.: Modelling the system behaviour of wet snow avalanches using an expert system approach for risk management on high alpine traffic roads, Nat. Hazards and Earth Syst. Sci., 5, 821-832, https://doi.org/10.5194/nhess-5-821-2005, 2005.