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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Multi-hazard risk assessment for roads: Probabilistic versus deterministic approaches" *by* Stefan Oberndorfer et al.

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We kindly would like to thank referee #1 for his/her efforts to go through 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):

General comments: The paper describes a comprehensive study for 3 main types of risk: risk for persons, property risk and risk for operational availability for mountain hazards (encompassing hydrological hazards, geological hazards and snow avalanches). The paper addresses relevant technical questions within the scope of NHESS. It contains new information about uncertainty of variables used for input to risk assessment

for roads to alpine hazards as well as application of probabilistic approaches within transport risk assessment. The methods are clearly described and based on risk equations according to ASTRA (2012) guideline. However, some of the assumptions within the paper would need more justification (e.g. choice of uncertainty bands for input parameters in risk calculation, i.e. why are upper and lower bands of the input parameters a good approach and where do the applied values for upper and lower bands come from?). The conclusion that the deterministic approach underestimates the risk compared to the probabilistic approach in this study is quite surprising, my experience is that use of deterministic approaches tend to overestimate the risk. The conclusion should be discussed and justified. The abstract contains some unprecise information and some clarifications are suggested. Some of the content should be better structured, to highlight the main contribution of the article and potential applications of the results.

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: Thank you for these comments. In a revised version, we will follow your suggestion and structure the article accordingly so that it will become more accessible. Specifically, we will split the current introduction section, introduce a new background section and extend the introduction section, as suggested.

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: Thank you for the comment. We understand that the point we would like to make here can be misunderstood. Hence, in a revised version we will revise this part of the abstract to make it more understandable. The changes foreseen for a revised version will go the following direction:

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 uncertainty in the input data. 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 in the 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: In a revised version we plan to 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 will 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: Thank you for this important comment. We will clarify this in the abstract and extend the discussion with the followings paragraph: 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.

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: Thank you for this comment. Indeed, there is a divide between academia and practical application that can only been closed slowly. We already discussed the applicability for improvement of road safety guidelines in the current version of the manuscript. In a revised version, we will put more focus on this and will provide 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 will clarify this issue and structure 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: Thank you for this comment. As indicated above, we will follow this suggestion and re-structure the manuscript accordingly. We will introduce a background section and extend 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: Obviously this sentence is unclear. For clarification we will change this to: "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: Good point. In a revised version of the manuscript we will move the sentence: "As shown in Fig. 2, the road segment is affected by three avalanche paths, four torrent catchments and one rockfall area." Another change will be made with respect to the subsequent statements: "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.". Both will go to the description of the study area.

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: Thank you for your comment. In the Appendix Tables A6 to A9 of the current manuscript version, the source of each variable is quoted. We will further extend the quotations 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 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 will supplement the manuscript 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 a revised version of the manuscript.

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