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Discussions

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Interactive comment on "On the nexus between landslide susceptibility and transport infrastructure – agent-based vulnerability assessment of rural road networks in the Eastern European Alps" *by* Matthias Schlögl et al.

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We would like to thank the referee for the thorough evaluation of our manuscript and the provided feedback. All of the feedback provided will certainly contribute to improve the quality of the manuscript.

Please find our responses below, with referee comments in italics, and authors' responses in standard format.

1 General comments

1. *In the tile, the paper implies an "... agent-based vulnerability assessment of rural road networks...". Unfortunately, this is not delivered, i.e. at the end of the paper, the reader does not have a clear answer on the question "How vulnerable is the road network (in Vorarlberg) towards landslide hazards?" Instead, 10 (very specific) Scenarios were analyzed and compared, considering the detour length and the evasion time. Hence, the concept how to assess network vulnerability has to be better expressed, beginning with a clear definition how the authors define vulnerability in their paper, and the introduction of some vulnerability measures for quantification and justification (e.g. using indices, curves, tables, maps, etc.).*

   The reviewer is right. We will adjust the title of the manuscript to indicate that the focus of this work is on the application of an agent-based transport model rather than on a vulnerability assessment of the network. The goal of this manuscript is actually to assess the vulnerability of the **agents**, not the vulnerability of the road network. Thus, the purpose of this manuscript is to demonstrate this approach, thereby highlighting the benefits of obtaining in-depth conclusions using spatio-temporally disaggregated mobility behaviour. See response to (3) for a more detailed description on that aspect. We will indicate this more clearly in the manuscript, including a definition of vulnerability as used in this context. In addition, we will adjust the introduction/motivation accordingly.

2. *Throughout the introduction, several times the importance of socio-economic impacts and the severe losses caused by the disrupting services are mentioned. Finally, only the prolongation of the travel is considered. Since the authors already implemented a very detailed agent-based model with many socio-demographic data (e.g. the agents are employed/unemployed), why not actually assessing the socio-economic impacts? This would also be a novel contribution of the paper, which is currently missing.*

The reviewer is right that this is an important issue in this context. We will add a more detailed analysis of select socio-demographic data (e.g. age, employment status) in the results section. Furthermore, we will re-phrase our introduction in terms of including a broader discussion on the use of ABM in natural hazards management. However, we would like to point out that although the underlying mobility patterns of the modelled agents are available, the transfer from their individual socio-economic features to comprehensive socio-economic impact values and resulting costs entails an extensive analysis in itself, which is methodologically different from the interdisciplinary basis that was presented in this paper. The travel time costs nevertheless provide a quantifiable indication that can serve as the basis for further analyses. The novel contribution of this work was to demonstrate the applicability of using spatio-temporally disaggregated mobility behaviour data for assessing the impacts on the local population rather than providing monetary quantification of impacts. We will discuss that in the manuscript and adjust the outlook section accordingly. In addition, we will emphasize the benefits and novelty of the approach by including daily evasion time heatmaps, illustrating the spatio-temporally disaggregated conclusions that only an agent-based approach allows for.

3. *In the current version of the paper, the methodology can be summarized as: "Running a traffic model, thereby disabling a selected link", which is not a novel concept, or method. What's missing is a clear description of the novelty for the proposed methodology. i.e. What is new? How is it better than other approaches?*

As mentioned in (2), we will highlight the novelty and the advantages of using an agent-based traffic model instead of a conventional (macroscopic) traffic model or even a simple network analysis. While several studies on network effects caused by disabled links do exist, we are not aware of a similar analysis that has been performed using an agent-based traffic model. The drawbacks of classical

aggregated (macroscopic) traffic models include:

- everything is just an indistinguishable flow → "gravity model ambiguities"
- modal re-decision can not be mapped w.r.t. each agent's properties
- flows are usually zone-to-zone, as larger spatial aggregation areas are used
- models are just trip-based, considering single "hops" from activity to activity, not whole day-plans
- more time-averaging and space averaging, therefor less policy-sensitive

As discussed above, the approach described in this manuscript alleviates such problems by employing an agent-based traffic simulation, which works on a disaggregated (finer) scale. We will clarify and emphasize this aspect in our method section in the manuscript.

4. *Concerning the landslide susceptibility map:*

   a *There is a conceptual flaw, using landslide susceptibility maps for assessing network-related processes. Contrary to building assets (e.g. houses, facilities, etc.), networks are used to describe dynamic processes (e.g. traffic flow), with the consequence that local events can have a severe impact on the whole network (as the authors showed in their example). The problem is that landslide susceptibility maps describe only the relative likelihood of future landslides, however, since the network is more than its components, there is a probability that a very unlikely landslide (low susceptibility), causes more harm than a very likely landslide. For example, there is a very low susceptibility that a landslide will be triggered and affecting a major connection, causing thousands of people to stay at home while incident 6 affects only 128 agents. At the current state of the paper, such network effects are completely neglected, however, this is the core concept (and challenge) of analysing network structures.*

C4

The selected incidents are used as scenarios to illustrate the applicability of the traffic model. To assert the realism of our assumptions, blockage locations were chosen based on the landslide susceptibility map. The goal was not to assess the worst effects (i.e. focusing on extreme landslides events), but the most likely blockages representing realistic everyday risks in this area (often a result of highly variable but very local thunderstorms during summertime), which in consequence were used as basis for assessing the impact on agents. We will clarify this in the manuscript.

b *Why did the authors develop a landslide susceptibility map although "The government of the province of Vorarlberg offers an official landslide susceptibility map..." (Page 5/ Line 26) and "The official hazard map already provides a reasonably accurate and consistent basis for the purpose of identifying vulnerable sections." (11/30)? Additionally, the used Weight of Evidence Method (Bonham-Carter, 1994) is nothing new, and therefore worth to spent 4 pages of the paper, only to figure out that the official landslide susceptibility map is a good enough estimate.*

Against the background of publication bias, we feel it to be our responsibility as scientists not to hide negative results, but rather to discuss them openly. In this case, our assumption that the application of the Weight of Evidence method would clearly improve the susceptibility map (as implied by various publications on this well-known method), was not met. Instead, our efforts to improve the official susceptibility map yielded only slight improvements. We found this outcome (which is largely due to the data quality of observed landslide events) to be worth mentioning and discussing. However, we do offer to improve on the landslide inventory data by performing a complete landslide mapping (polygons) from satellite images for the whole study area. Subsequently, a new landslide susceptibility map will be calculated again, using these new input data.

C5

5. *Concerning the selection process of links to be blocked*

   a *It is absolutely not clear, how the 12 incident sides were selected. Please, give a detailed description how this was done (quantitative?, qualitative?), especially since the authors remove later on selected sides ("... 12 had to be removed due to its close proximity to Silvretta-Hochalpenstraße ..."(13/1).)*

   We agree with the reviewer that this is unclear. We will clarify the incident site selection procedure.

   b *Also, it would be of interest which landslide susceptibility is associated with each incident side. See point 5: If only areas with high susceptibility are considered, the question arises, if there is not a scenario where the road network is more vulnerable to landslides in less susceptible areas.*

   We will include the landslide susceptibility values for each incident into Table 2.

   c *An important part missing is the interaction between landslides and road network. In the current version, it is assumed that a landslide occurs at the incident side and completely damage (block) the road section over a period of at least 24 hours (runtime for the MATSim model)? If so, these are very strict assumptions and is contradicted by the author's statement "...due to the fact that landslides, which affected traffic routes or (agri-)cultural areas, are usually fixed quickly and efficiently." (12/10). Also, how could such assumptions be made without the knowledge of the particular landslide type (initiation and run-out, volume, speed)? The likelihood of the occurrence of landslides is not a sufficient reason to assume a damaged infrastructure. Please, specify the assumptions made and give a detailed description how the (physical) damage of the infrastructure was derived from a landslide susceptibility map.*

   The reviewer raises an interesting point in pointing out that the likelihood

of the occurrence of landslides is not a sufficient reason to assume a damaged infrastructure - especially, if in-depth knowledge of the event is lacking. However, we would like to emphasize again that the focus of this study is on the application of an agent-based traffic model to model responses in case of capacity reductions of a regional scale road network. We argue that occurrence probability of landslides is a reasonable proxy for assuming likely network interruptions that are representative of common, everyday risks in the study area. While the primary road network is indeed very resilient to landslide exposure, rural road networks are way more susceptible to landslide occurrences (since the high building standards for highways cannot be met on all rural roads). Complete interruptions caused by landslides are just one possible scenario to obtain blockage points. The described methodology also allows to specify capacity reductions (e.g. 50% capacity if only one lane is blocked). We would like to point out that we put the focus on assessing the whole federal state using several likely incident locations with a predefined (simple) interruption scenario instead of focusing on one or two locations with different varying blockage duration and capacity reduction patterns. Please note that the statement that roads are "usually fixed quickly and efficiently" does not mean that roads are fixed instantly. For safety reasons (and of course the FRC of the road), interruptions of at least 1-2 days are common for high level roads. Interruptions of several days are common on the rural road network in Austria. This is well within the assumptions made in this study. Finally, modelling physical damage is no focal topic of this manuscript. Landslides are merely considered as a scenario to obtain blockage points.

6. *Concerning the agent-based traffic model*

   a *The implementation of an agent-based model is very ambiguous, please clearly state why such an approach was used, especially since most of the*

*results (affected persons, detour lengths, evasion times) could also be ob-
served by a flow-based traffic assignment.*

We can understand the confusion regarding the differences, but have to un-
derline that the comment of the reviewer is not true as stated. We will clarify
this as requested by the reviewer. The main benefit is in the temporal and
spatial disaggregation of information on agents, which are lost in the flow of
conventional transport models. See response to (3).

b *In the current version of the paper, several assumptions made and several
limitations of the traffic model are not clearly stated. e.g. the MATSim sim-
ulation considers only/maximum one day, an agent has perfect knowledge
of the interrupted section, origin and destination do not change during and
after extreme events, etc.*

This is only partly correct. The agents do not have perfect knowledge of the
interrupted section initially. They only acquire this knowledge iteratively as a
whole population after optimizing for best route user-equilibria. Most of the
limitations are discussed in the manuscript (18/6ff). We will further clarify
these aspects mentioned by the reviewer.

c *A major shortcoming is that only trips of inhabitants of Vorarlberg are consid-
ered, which does not reflect reality and certainly leads to an underestimation
of the socio-economic impacts in the region. The question is how can the
vulnerability assess given this constraint? Additionally, how could the traffic
model be calibrated and validated, neglecting a majority of the travellers on
the network?*

This may indeed be considered a shortcoming. However, it is also clearly
stated as such in the manuscript. Conducting mobility surveys is extremely
resource-intensive. In the said case study region, we would need similar mo-
bility survey data for Germany (Bavaria), Switzerland (Cantons of St. Gallen
and Grisons), Liechtenstein and the Austrian federal state of Tyrol to cover

all adjacent countries/regions. Given the resources at hand, and since the focus is on the impacts of network interruptions on the local population (user level), we consider this model to be useful despite certain restrictions (i.e. likely underestimation of the impacts). Also, the fidelity of any model is restricted toward the boundary areas. In addition, it can hardly be argued that "a majority of travellers on the network" are neglected. Only the two highways, A14 and S16, can be considered major transit routes in the area, a majority of commuter travel on rural roads is definitely captured by the underlying mobility survey data.

d *Why was so much focus put on introducing and analyzing 10% scenarios, without any additional benefit for doing so? It could have been stated, that for computational reasons a pre-sampling with 10% of the agents has been done, but the evaluation has been done with a 30% scenario.*

The official guidelines state that 10% is a reasonable subset of the full population to model all relevant effects. However, results of the subsequently used 30% sample show different implications, as discussed in the manuscript. This is particularly the case for the variance of the results, which increases (!) with increasing sample size. We consider this to be an interesting discovery, since this questions the general recommendations. We will clarify this in the manuscript.

e *It is not clear how many simulations (not iterations) have been done for each incident. In other words, how often was the traffic model run for one incident? Since the agent-based model tries to optimize the behaviour of multiple agents, the simulation results might change over time.*

For computational reasons, each simulation was only done once. The model could be re-run multiple times using different random seeds. While this might provide better insights with respect to analyses of specific incidents by reducing uncertainty of the results, this does not affect the applicability of the

demonstrated approach. We will add this information to the manuscript.

f *Using advanced modelling tools often suggests precise outcomes, however, since many unknown input parameters are necessary, the results might come with high uncertainties. These uncertainties have to be quantified in order to make meaningful statements. At least a more detailed (quantitative) description how accurate the traffic model compared to the actually measured traffic volumes should be given.*

The core purpose of any traffic model tool is to provide predictive models (based on partially known real-world data) for scenario estimation, rather than precisely calculate exact values. Reliability based on comparisons with traffic count data is also limited, since these data are only valid for a very specific location and are likely to change at the next crossroads. In addition, traffic count data are also subject to high uncertainties (as they are often extrapolated from a measurement period of e.g. 2 weeks). Also, KPI values for assessing the quality of traffic models are not yet available, but currently still under development. The whole question can thus be broken down to "systematics vs. statistical uncertainties". We argue that discussing systematics is more important in this context. The uncertainties of any traffic model are rather grounded in the quality of the input data rather than in the model itself. Therefore, classical uncertainty quantification (e.g. in terms of Monte Carlo simulation using multiple model runs to obtain a distribution of results) often does not provide substantial insights. In addition, this kind of uncertainty assessment would be computationally prohibitive for the present study when using a sufficiently large number of scenario runs for all incident scenarios.

However, we consider this issue a valuable question which is intended to be answered in future work.

7. *As mentioned in the beginning, it is hard to interpret the results and conclude*

how vulnerable the road infrastructure is. For example for side incident 10, 4709 agents are affected by an average evasion time of 3:10 minutes over a whole day. Does this mean there is almost no vulnerability against landslides? How can road authorities derive conclusions from this results? Should they invest in some protection measures or not?

The first order interpretation of this result is correct. Road blockage of incident 10 has only minor effects on the traffic displacement in this area. We will add an additional subsection on vulnerability assessment to the discussion section to explore this issue further in the manuscript.

2 Specific comments/questions

1. *(1/10): "The focus of this case study is on resilience issues and support for decision making in the context of a large-scale sectoral approach." this is clearly not the case in this paper. Either this will be added to the paper of this statement should be deleted.* The reviewer is right. We will adjust this statement accordingly.

2. *(1/15) Here only single events are considered, however, in reality, we often have to deal with the occurrence multiple hazard events (e.g. heavy rainfall caused several landslides). How can the proposed methodology cope with such situations?*

   From a methodological point of view, this is not different from what was done in the present study. Expanding the methodology accordingly is simple: instead of removing a single link from the routing graph, multiple links can be removed, and the model can be re-run on these modified graphs.

3. *(7/23) "Road capacity was derived from the functional road class." For personal interest, how was this done and in which range where those values per road*

class?

Road capacity was estimated from the FRC attribute of the OSM graph:

```
def get_capacity_per_lane(frc):
    if frc == 0:
        return 2000
    if frc == 1:
        return 1500
    if frc == 2:
        return 1200
    if frc == 3:
        return 1000
    else:
        return 500
```

4. *(10/1) Figure 1. The different road classes should be indicated (e.g. highway, primary road, ...) in order to give the reader an overview how the network is structured and where the major links are located. Additionally, since the base scenario is already computed, a map with the traffic volume should be added, to indicate the traffic flow. Next, to such a figure, it would be interesting to see a figure for the traffic volumes of an interrupted network.*

   We will add information on road classes as well as maps as proposed by the reviewer. In addition, we intend to provide additional supplementary material in an openly accessible repository, including e.g. time-lapse videos of traffic flow across the whole day.

5. *(14/3) "In some situations, the blockage of a non-redundant link can occur, meaning that no alternative routes are available, as is the case for incident 11. Here, it is of no benefit to run a traffic simulation on the modified road graph affected by the landslide event." Actually, what would happen is that the overall travel time*

will decrease for the network since fewer people are on the roads. The issue of missed trips (people who are cut off from the network) is neglected in the current version of the paper, however, it is important problem and should also be treated. Especially since this could cause more socio-economic impacts than a trip prolongation of several minutes.

While this is theoretically correct we do argue that this is only of minor relevance. For a vast majority of links in the network alternative routes do exist, and the rare cases where complete blockages would result in a complete cut-off the agent-based traffic model does not offer any additional benefit over simpler traffic models. The assessment scheme would be different than on the other scenarios.

6. *(15/9) How many agents were simulated? 30% of 260000 is 78000 and not 5518. Probably this sentence has to be clarified.*

   We will add this information to the manuscript and clarify this sentence as proposed by the reviewer.

7. *(16/1) Figure 2. Why showing the 10% and the 30% example, is there any additional value in showing and discussing the 10% example?*

   See response to (6d).

8. *(19/4) "In this paper, we have shown that agent-based traffic modelling allows gaining interesting insights into the impacts of road network interruptions on the mobility behaviour of affected communities by modelling their responses to network disturbances."This might be true but is only slightly related to the topic of road network vulnerability which was promised in the title of the paper.*

   This is correct. As mentioned above we will adjust the title of the manuscript to clarify.

Again, we would like to thank the reviewer for the thorough review and the helpful

feedback provided. These comments will certainly contribute to improve the quality of the manuscript.

Overall, we feel that meeting all suggestions by the reviewer would be beyond the scope of a single manuscript. Covering the whole methodological chain from detailed landslide process simulation, agent-based traffic modelling (including various combinations of single link and multiple link failures for different values of section vulnerability), network vulnerability assessment, socio-economic analysis of consequences and provision of decision support as well as recommendations for road authorities would simply break the mould. While we do intend to incorporate a vast majority of the reviewer's suggestions, we hope that our responses do clarify why certain suggestions cannot be met.

To summarize: Our approach is based on certain assumptions and scenarios, which allow to illustrate the application of an agent-based traffic model to obtain the consequences of network interruptions (in terms of detour statistics) on the local population, by using actual mobility survey data. This manuscript is intended to serve as a methodological blueprint covering an interdisciplinary process chain from landslide susceptibility modelling via agent-based traffic modelling to an agent-specific vulnerability assessment. Thanks to the insightful reviewer comments we will add a more concise description of the process flow, including a more detailed assessment of a selection of socio-demographic variables to illustrate the advantages of an agent-based model. We are fully aware of the fact that the approach can of course be extended, e.g. by including cross-border traffic, assessing capacity reductions instead of complete blockages or assessing multiple link failures at the same time. However, all these aspects are not in the focus of this study, as they are merely methodological extensions of the approach we present here.

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