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Assessing volcanic risk to transport networks – The case of Merapi, Indonesia

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ABSTRACT

Recent eruptions have demonstrated the inadequacy of current volcanic ash contingency plans (VACP) to maintain transport performance at acceptable levels. A significant contributor to this situation results from the fact that there is currently no methodology to comprehensively assess risks to the transport sector and therefore no way of establishing risk based scenarios with which to compare different VACP strategies. This paper presents a framework that quantifies the risk to the transport sector from volcanic ash events and therefore can be used to evaluate the efficacy and efficiency of transport infrastructure contingency plans. The model consists of an exposure module of relevant transport infrastructure, two hazard scenarios, specifically ~5-year event and ~100-year event, a road operability curve relating maximum safe speed with depth of volcanic ash and settling rate, and a traffic flow model that calculates normal and disrupted travel times. The final model is applied to the region around the city of Yogyakarta which is threatened by the Merapi volcano. The simulations demonstrate how the model is able to calculate increases in travel times due to volcanic eruptions. While we have considered volcanic hazard, we describe how the framework can be applied to seismic hazard using earthquake intensity information.

1 INTRODUCTION

Volcanic hazard is one of the more poorly understood threats that can disrupt transport provision for communities. It is estimated that more than 800 million people live within 100km of active volcanoes (Loughlin et al., 2015) and recorded data of the impacts of volcanic eruption show that the ash produced by volcanic activity can be a significant hazard to transport infrastructure, with the accumulation of only a few millimetres of volcanic ash disrupting transport services considerably (Wilkinson et al. 2012).

The erupting Eyjafjallajökull volcano in 2010 is a contemporary examples that illustrates how volcanic ash from a moderate eruption can have a substantial financial impact on the transportation sector. This modest-sized eruption caused the most extensive air travel shutdown since World War II (SMH, 2010) and was shown to be disproportionately disruptive to air traffic networks (Wilkinson et al. 2012). The economic loss suffered over one month following this event was estimated to reach around €3.3 billion (Ragona et al. 2011). Additionally, 110,000 flights were cancelled (DSB 2013), more than 10 million passengers suffered delays and 313 airports (equal to 80% of the European air network) were disrupted (ACI-Europe 2010). Globally, from 1944 to 2006 at least 101 airports in 28 countries were disrupted on 171 separate occasions due to 46 volcanic eruptions of which most effects were due to volcanic ash (Guffanti et al. 2009a).

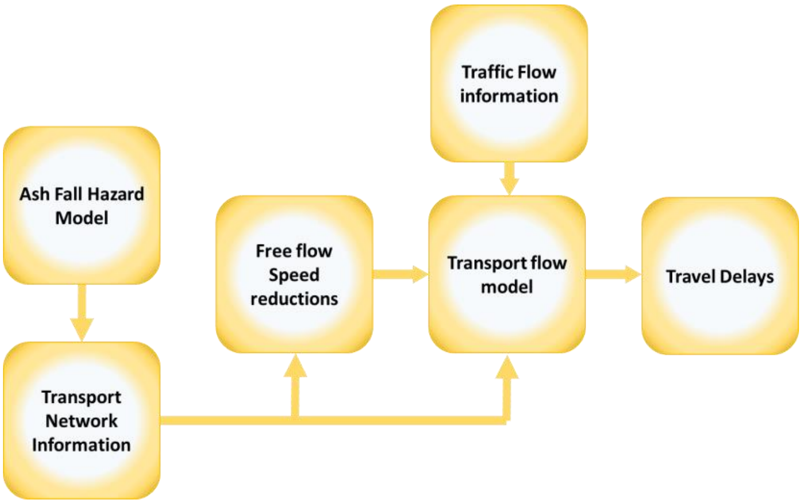
Ash presence on road networks can also cause inoperability of roads or considerably reduce traffic speeds (Johnston and Becker 2001, Wilson et al. 2014) as a result of three common causes, i.e. skid resistance reduction, road marking coverage and visual range reduction (Blake et al. 2016a). Moreover, visibility may be reduced due to falling material or through the remobilisation and resuspension of deposits into the atmosphere, either naturally (by wind) or due to human activities, such as vehicle movement and cleaning processes (Blake et al. 2018). The above information would suggest that a methodology for estimating disruptions to travel networks due to volcanic hazards would be a useful tool in managing volcanic risk Estimating risk to insurance portfolios due to natural hazard is usually calculated using a Catastrophe Models (CAT) and while these have been very successful for building assets, they are rarely applied to estimate potential losses to infrastructure. The reason for this is that infrastructure is often self-insured and therefore provides little incentive for insurance companies to develop models to estimate loss and secondly, in the case of infrastructure networks, exposure databases are interlinked where damage to one component in the network can have a significant knock on effect for other parts of the network. For this reason traditional CAT models are unable to capture the full range of impacts on these networks. While some work on loss models for transport networks has been conducted (Dunn and Wilkinson 2017), (Pregnolato et al. 2017), (Fu et al. 2017) and (Panteli et al. 2017) to the best of our knowledge they have not been applied to volcanic hazard. In this paper we present a framework for estimating increases in travel times due to volcanic ash events and demonstrate its merits by applying it to travel between airports on the island of Java in Indonesia in the region of the Merapi volcano.

2 THE MODEL

The proposed volcanic ash transport CAT model presented in this paper is given in Figure 1. The various elements of the model are typical of a Cat model; with the exception that impacts are measured in terms of travel delays. Calculation of this metric requires the inclusion of a transport model that considers how transport movements may be altered due to tephra ejections.

2.1 Hazard Model

The hazard module was developed by modifying the volcanic hazard model of Jenkins (2017a, b). The tephra advection-diffusion model TEPHRA2 (Bonadonna, 2005) was used to probabilistically simulate the transport and fallout of tephra (including ash) for two scenarios of differing volcanic explosivity index (VEI) at Merapi volcano. The first scenario is a VEI 2 eruption, which has an ~4-6 year return period (Thouret et



al., 2000). The second scenario is the 2010 (paroxysmal phase on 5 November) VEI 4 eruption, which is regularly reported as a 100-year event (e.g. Surono et al., 2012). These scenarios were modelled with mid-range VEI volumes (from the log scale), following the VEI assignation of Newhall and Self (1982). To provide a realistic tephra fall footprint, we simulated both scenarios into a past wind condition at Merapi: 6 am on 5 November 2010. This time is considered to be approximately

Figure 1: Transport Catastrophe model

accurate for the 2010 eruption, as the first part of the paroxysmal eruption starting at midnight with mostly pyroclastic density currents. Wind speed and its direction with height above the volcano were sourced from the ECMWF ERA-Interim reanalysis database (Dee et al., 2011) for the grid cell closest to Merapi.Merapi at 6 am on 5 November 2010. This time is considered to be approximately accurate for the 2010 eruption, as the first part of the paroxysmal eruption starting at midnight with mostly pyroclastic density currents. Wind speed and its direction with height above the volcano were sourced from the ECMWF ERA-Interim records.

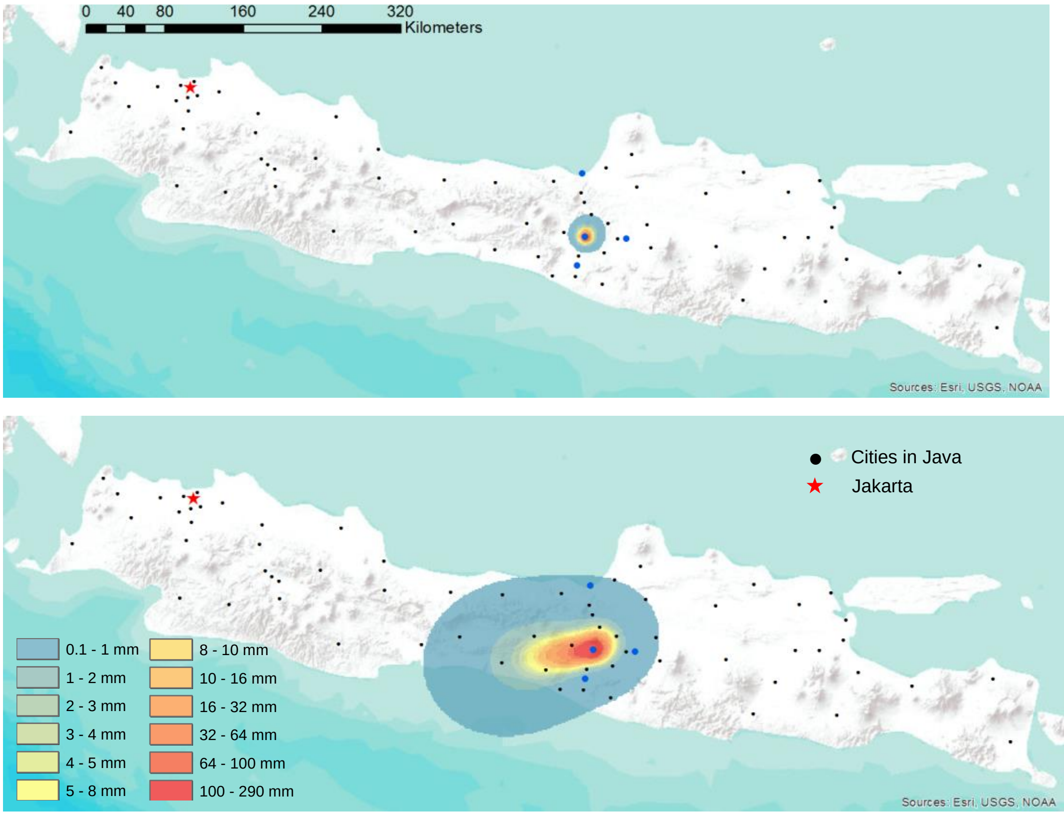


Figure 2: Ash Intensity for Merapi VEI 2 and VEI 4 Eruption Scenarios in the Context of Java Island. The gradation colour represents the thickness of the ash deposit on the ground. The cities which are presented as black dots are the cities with a major economic contribution to Indonesia's national economy (GO 26/2008, 2008). Jakarta, notated as the red star, is the capital of Indonesia.

2.2 Transport Model

2.2.1 Merapi Transport Network

Merapi is enclosed by three major cities in Indonesia, namely Yogyakarta, Surakarta and Semarang. These three cities have been considered as origin and destination simulation points in our analysis as they each have an airport and so can be used to assess potential increases in travel time due to one airport closing.

The road network and the associated data to define its capacity (i.e., land use, building density and slope) were downloaded from Indonesia Geospatial Information Agency (tanahair.indonesia.go.id) in shapefile format. The number of vehicles within each corridor were collected from the JICA (2009) traffic survey and are presented in Table 1.

Table 1: The Length and Number of Vehicles for Each Corridor/Sub-Corridor in the Case Study (adapted from JICA (2009))

Corridor	Direction	Length	Number of Vehicles				
			Standard Vehicle[1]	Medium Vehicle[2]	Large Bus[3]	Large Truck[4]	Motor Cycle
1	Yogyakarta – Surakarta	52.3km	1126	62	81	44	2347
	Surakarta – Yogyakarta	52.3km	1111	57	80	43	2287
2	Surakarta – Semarang	93km	307	26	40	32	388
	Semarang – Surakarta	93km	347	23	35	27	413
3	Semarang – Yogyakarta	125.6	657	43	66	27	937
	Yogyakarta – Semarang	125.6	737	41	61	26	1132

[1]Including cars and pickup cars - two-axle, [2]Including small buses and trucks - two-axle, [3]Including medium and large buses, [4]Including three-axle trucks and more.

An overview of the road network around Merapi Volcano and the case study cities presented in Figure 3.

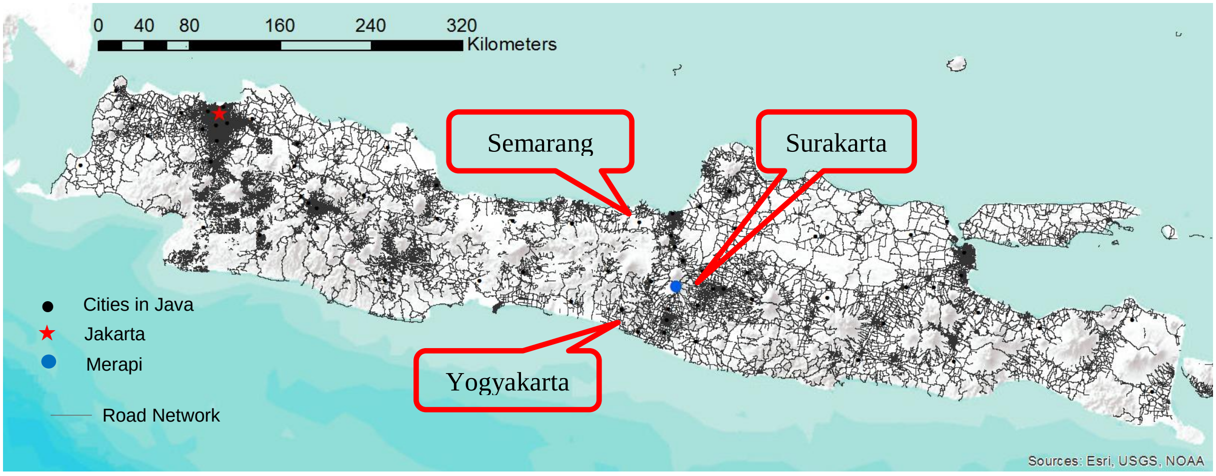


Figure 3: The Road Network around the Case Study Cities

2.2.2 Transport Model.

The simplified traffic flow model is based on the Indonesian Highway Capacity Manual (IHCM, 2014) and is used to determine the average speed in each section of the transport corridors. In our work we have considered reductions in speed due to congestion (i.e. the average speed is defined by assigning the Degree of Saturation to the free-flow speed in normal condition) but have ignored delays due to the influence of traffic passing through road junctions. We argue that this simplification is not likely to be significant as most of the roads on the shortest path are categorised as highways. The travel time in normal condition is calculated based on assigning traffic to the shortest path between the airports belonging to all three cities calculated using Dijkstra algorithm.

In terms of the traffic management measures, there are two strategies to be tested in the disrupted conditions: normal route with traffic speed reduction and rerouting to the less or not impacted route but with an increase the distance. In this paper we are only considering speed reduction strategy

2.2.3 Transport operability curves.

Transport operability curves (relationships between hazard intensity and transport operations e.g. speed) have been developed for flooding (Pregnolato et al. 2017); however, o the best of the authors' knowledge there are currently no relationships between travel speeds and ash intensity (depth and/or settling rate) with the exception of Rezki-Hr (2019) who has developed road operability curves by combining available laboratory experiment results of Blake et al. (2017, 2018) and Wilson et al. (2017) and road safety standards. This curve is able to recommend the maximum safe speed for driving on the road experiencing volcanic ash of a specific intensity (both depth and settling rate) with 100mm of ash defined as the passability threshold of the road. These curves were used to calculate free flow speed reductions due to the two hazard scenarios considered in this paper. Further details of these relationships, how they were developed and the relevant validation material can be found in Rezki-Hr (2019).

3 RESULTS: ROAD TRAVEL TIME DUE TO SPEED-REDUCTION STRATEGY

The results of the travel time delay calculation due to speed reduction using the same route are presented in Figure 4 for VEI 2 and Figure 5 for VEI 4.

As illustrated in Figure 4, VEI 2 only disrupts the link (shortest path) between Surakarta and Semarang (corridor 2) with ash that is 1mm thick. However, as the maximum speed suggested by the operability curve due to 1mm thick ash is higher than the basic free-flow speed in this affected area, the travel time in this VEI 2 scenario is the same as normal time. The same thing happens with Corridor 1 in the VEI 4 scenario where the presence of ash that is 1mm thick does not cause any delay (Figure 5). However, the VEI 4 eruption increases the travel time in Corridors 2 and 3 (see Figure 5) significantly, from 150/153 and 265/208 minutes to 205/208 and 307/287 minutes respectively (the slash divides both directions in the same corridor). In other words, it causes a delay of 55/55 minutes per passenger car in Corridor 2 and 42/79 minutes per passenger car in Corridor 3. Although in the VEI 4 scenario there are twenty-four different segments of the road in Corridor 3 that are covered by >100mm of ash, in this analysis it is considered that this corridor is operational because the length of the segments which are covered by this thickness of ash is not significant (211m average length). The travel delays for passenger cars travelling between airports are summarized in Overall, the simulation showed that the Merapi VEI 2 eruption does not cause any delay in all three corridors, despite the presence of 1mm of ash in Corridor 2. In the VEI 4 eruption, all the corridors remain passable, but the road users will experience a significant delay (up to 38%) in Corridors 2 and 3, while Corridor 1 is unaffected (no delay).

Table 2.

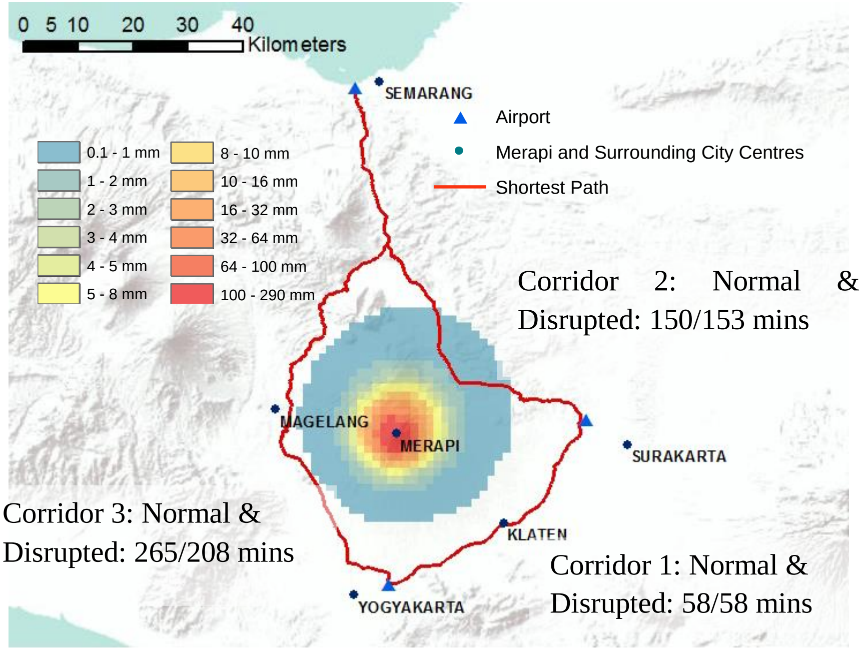


Figure 4: The Travel in Normal and Disrupted (Merapi VEI 2 Eruption) Conditions in All Corridors. The text inside the box indicates the travel time, while the slash symbol divides the travel time in two different directions in each corridor. Please refer to Overall, the simulation showed that the Merapi VEI 2 eruption does not cause any delay in all three corridors, despite the presence of 1mm of ash in Corridor 2. In the VEI 4 eruption, all the corridors remain passable, but the road users will experience a significant delay (up to 38%) in Corridors 2 and 3, while Corridor 1 is unaffected (no delay).

Table 2 for the corresponding direction.

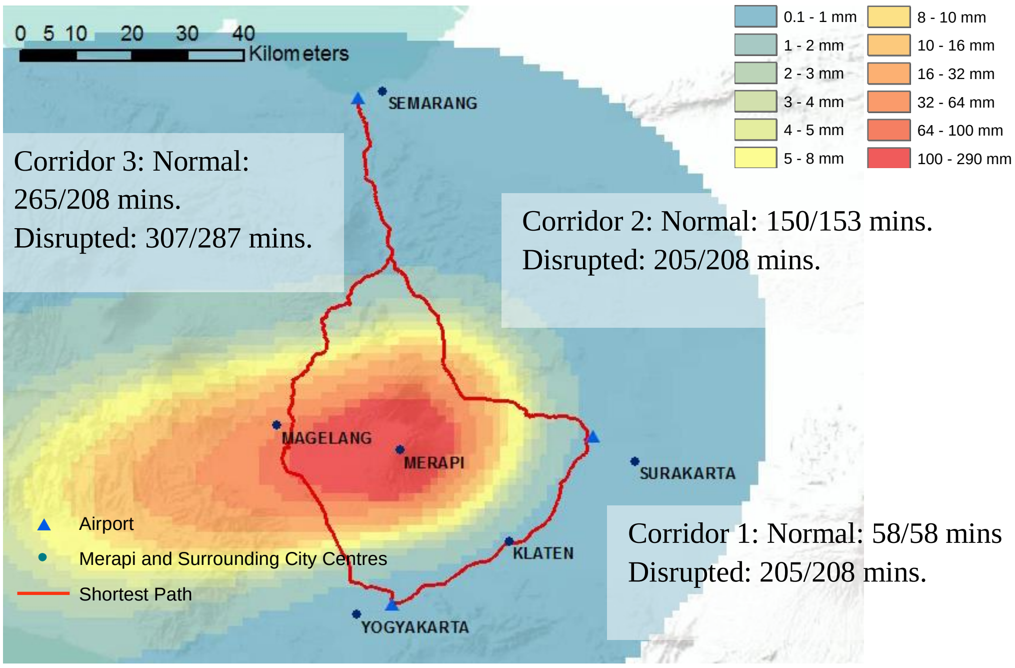


Figure 5: The Travel in Normal and Disrupted (Merapi VEI 4 Eruption) Conditions in All Corridors. The text inside the box indicates the travel time, while the slash symbol divides the travel time in two different directions in each corridor. Please refer to Overall, the simulation showed that the Merapi VEI 2 eruption does not cause any delay in all three corridors, despite the presence of 1mm of ash in Corridor 2. In the VEI

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Table 2: The travel time in all three corridors if the speed-reduction measure is imposed and the traffic continues on the same route. The numbers in the brackets indicate the increase from the normal conditions.

Corridor Number	**Direction**	**Normal Travel Time (minutes)**	**Disrupted Time (minutes)**	
			VEI 2	**VEI 4**
1	Yogyakarta – Surakarta	58	Normal	Normal
	Surakarta – Yogyakarta	58	Normal	Normal
2	Surakarta – Semarang	150	Normal	205 (55)
	Semarang – Surakarta	153	Normal	208 (55)
3	Semarang – Yogyakarta	265	Normal	307 (42)
	Yogyakarta – Semarang	208	Normal	287 (79)

4 CONCLUSIONS

A Catastrophe type model for transport networks impacted by volcanic ash has been presented. The model extends typical CAT models by using a transport model to calculate transport delays and develops transport operability curves which relate reduction in travel speeds to ash thickness and settling rates. The impacts of two ash events were presented to show how the model can give detailed information on transport disruptions. The greater of these two events resulted in travel time increases for each passenger of up to 79 minutes (38% increase) in the Yogyakarta-Semarang corridor. While we believe that the model is very valuable in managing volcanic risk, there are still a number of uncertainties in determining what delays may be expected. The largest of these are the provision of road operability functions that relate travel speeds with ash intensity. We believe that the relationships we have used are the best currently available but would encourage other researchers to help us to improve them by collecting more calibration data. While we have considered volcanic ash events, the method could equally be applied to earthquakes – for example increases in travel times due to road settlement caused by liquefaction; however, operability curves that relate travel speeds to liquefaction intensity would need to be developed. Similarly other infrastructure such as electricity supply could be considered by replacing the transport model with a power distribution model.

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