IMPACTS OF VOLCANIC ASH ON ROAD TRANSPORTATION: CONSIDERATIONS FOR RESILIENCE IN CENTRAL AUCKLAND

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ABSTRACT

Auckland is built on an active volcanic field. During a future volcanic eruption, functional transport networks will be critical for evacuations, as well as for immediate and long-term recovery once direct threats have subsided. Ash is generally the most disruptive and widely dispersed volcanic hazard, potentially impacting road transport networks for months to years. In Auckland ash may originate from both local eruptions and those further afield in the North Island.

Common ash impacts on roads include:

- Skid resistance reduction
- Road marking coverage
- Visual range reduction

Few studies have attempted to quantify these impacts in detail, particularly for ash <10 mm thick. This research involves the conception and implementation of a series of experiments in the Volcanic Ash Testing Laboratory (VAT Lab) at the University of Canterbury to provide quantitative data relating ash characteristics to road transport impact types.

The results, along with empirical evidence and expert advice from staff at transport organisations, are being used to inform models of disruption across Auckland's road network following hypothetical eruptive scenarios. Findings can be used to improve evacuation planning and clean-up strategies, and provide safe operating thresholds and specific travel advice for future ashfall events, increasing transport system resilience.

1. INTRODUCTION

Functional transport networks are critical for society both under normal operating conditions and in emergencies. During volcanic eruptions, transport networks may be required for the evacuation of residents and to allow sufficient access for emergency services to enter affected areas. Once direct threats have subsided, transport networks are crucial for both immediate and long-term recovery including the clean-up and disposal of pyroclastic material, and restoration of services. To increase resilience to volcanic hazards, it is thus imperative that effective transport management strategies are incorporated into contingency planning in areas where society and infrastructure are at risk (e.g., Auckland, New Zealand; Kagoshima, Japan; Mexico City, Mexico; Naples, Italy; Yogyakarta, Indonesia).

Volcanic eruptions produce many hazards. Damage to transport from proximal hazards such as lava flows, pyroclastic density currents and lahars is often severe, leaving routes impassable and facilities closed. Volcanic ash (ejected material with particle sizes <2 mm in diameter) is widely dispersed and, although not necessarily damaging to the static transport infrastructure, is generally the most disruptive of all volcanic hazards (Johnston & Daly 1997). Even relatively small eruptions are capable of widespread disruption, which may continue for months due to the remobilisation and secondary deposition of ash by wind, water, traffic or other human activities, even after an eruption has subsided.

To date, studies on the impacts of volcanic hazards to society have focussed on the effects of ash (e.g. Blong 1984; Wilson, Daly & Johnston 2009a; Wilson et al. 2011; Wardman et al. 2012a; Wilson et al. 2012a; Wilson et al. 2014). These studies and reports suggest three frequently occurring types of volcanic ash impacts on surface transport, with notable eruptions that have led to such impacts highlighted in Table 1:

1. Reduction of skid resistance on roads covered by volcanic ash.
2. Coverage of road markings by ash.
3. Reduction in visual range during initial ashfall and any ash re-suspension.

Despite much anecdotal evidence, there has been little work to quantify the impacts of ash on surface transport. Quantitative, empirical evidence could inform road management strategies in syn-eruptive and post-ashfall environments such as evacuation planning, safe travel advice in the recovery phase and recommended clean-up operations.

Existing studies of exposed critical infrastructure have generally focussed on very large eruptions and ashfall deposits >10 mm thick, rarely reporting the effects from ashfall <10 mm thick (Wilson et al. 2012a). This presents a source of uncertainty for emergency management planning and loss assessment models, which is important, as thin deposits are more frequent. Indeed, the limited quantitative data available from historic observations generally relates impacts to approximate depths of ash, which may not be the best metric: ash characteristics such as particle size, ash type, degree of soluble components and wetness, may influence or even control surface transport impacts. We investigate the importance of these alternative characteristics in this study.

Here, we present experimental methods and results to date from the University of Canterbury's Volcanic Ash Testing Laboratory (VAT Lab) on the three frequently occurring impacts to surface transportation. All laboratory techniques have been developed in the context of Auckland's motorway and arterial road network and results can be used to provide safe operating thresholds and specific travel advice during future ashfall, thus increasing overall transportation system resilience. We briefly summarise how the findings are being used to inform models of disruption and recovery across Auckland's road network following hypothetical eruptive scenarios in the Auckland Volcanic Field.

Volcano	**Year**	**Ash depth (mm)**	**Skid resistance observations**	**Road marking coverage observations**	**Visibility observations**
Ruapehu	1945				Bus headlamps blacked out by thick ash[1]
Ruapehu	1945				Re-suspended ash similar to dust produced on unsealed roads[1]
St Helens	1980	>1		Drivers disorientated due to loss of markings[2]	
St Helens	1980	17	Ash became slick when wet[3,4,5]		
St Helens	1980	40			Flares used to guide people[6]
Hudson	1991		Traction problems from ash on road[7]	Road markings obscured[7]	
Hudson	1991	20-50			~1 m visual range a week after eruption ("transport virtually closed down")[7,8]
Hudson	1991	200-300			People couldn't drive partly due to visibility[7]
Spurr	1992	3			Visibility reduced until rain alleviated issues[1,9]
Unzen	1992				Visibility reduced by suspended ash[9,10]
Tavurvur and Vulcan	1994	1000	Vehicles stuck in deep ash, passable if hardened[9,11,12]		
Ruapehu	1995-96	"thin"	Slippery sludge from ash-rain mix[1,9]	Road markings obscured[1,9]	Reduced visibility (roads closed)[1,9]
Montserrat	1997		Rain can turn particles into slurry of slippery mud[13]		
Etna	2002	0-2			Ash remobilisation by traffic and wind caused reduced visibility[9]
Etna	2002	2-20	Traction problems, damp & compacted easier to drive on[9]		
Reventador	2002	2-5	Vehicles banned due to slippery surfaces[9,14]	Vehicles banned due to covered road markings[9,14]	
Chaitén	2008		Reduced traction caused dam access problems[15,16]		Reduced visibility caused dam access problems[16]
Chaitén	2008	~300			10-15 m visibility (people drove cautiously)[15]
Merapi	2010		Slippery roads caused accidents & increased journey times[17]		
Pacaya	2011	20-30	Slippery roads with coarse ash[18]		Difficult to drive due to impaired visibility[18]
Puyehue-Cordon Caulle	2011	>100	2WDs experienced traction problems (wet conditions)[19]		"No visibility"[19]
Shinmoedake	2011				Reduced visibility (roads closed)[20]
San Cristóbal	2013				Visibility greatly reduced ~15 km from vent (headlights used)[21]
Sinabung	2014	80-100	Road travel impracticable in wet muddy ash[22]		
Kelud	2014				Reduced visibility[23]
Calbuco	2015	~50			Visibility reduced to 500 m around 100 km from vent[24]
Sakurajima	1955-2015	>1	Roads slippery, perhaps less so with recent fine ash[9,25,26]	Road markings obscured[9,20,25,26]	

Table 1. Examples of reduced skid resistance, road marking coverage and reduced visibility following volcanic eruptions ([1]Johnston 1997; [2]USGS 2013; [3]Warrick et al. 1981; [4]Cole & Blumenthal 2004; [5]Cole et al. 2005; [6]Blong 1984; [7]Wilson et al. 2009b; [8]Wilson 2009 (unpublished field notes); [9]Barnard 2009; [10]Yanagi, Okada & Ohta 1992; [11]Stammers 2000; [12]Nairn 2002; [13]USGS 2009; [14]Leonard et al. 2005; [15]Wilson 2008 (unpublished field notes); [16]Wilson et al. 2012b; [17]Jamaludin 2010; [18]Wardman et al. 2012b; [19]Wilson et al. 2013; [20]Magill, Wilson & Okada 2013; [21]GVP 2013; [22]Volcano Discovery 2014; [23]Blake et al. 2015; [24]AccuWeather 2015; [25]Durand et al. 2001; [26]Kagoshima City Office (2015, pers comm)). There may be other instances described as 'general impacts to transportation' or which have not been recorded in available records.

2. STUDY AREA – AUCKLAND

Auckland, with a population of 1.42 million as of June 2013 (Statistics NZ, 2013), is the largest city in New Zealand and a vital link in the country's economy. A smoothly operating transport network in Auckland is important for both the regional and national economy (AELP-1, 1999). However, central Auckland is built on a narrow isthmus between the Waitemata Harbour to the north-east, and Manukau Harbour to the south-west. This forms a major geographical feature of the city, constraining the location of many lifeline utilities including electricity, communication and transportation networks, and limiting land-based evacuation routes (Auckland CDEM 2015). Many utilities running through the Auckland isthmus service high populations and consequences of any disruption may be widespread.

Auckland is built on the 360 km^2 active intra-plate Auckland Volcanic Field (AVF) (Figure 1a-b). The geologically recent eruption of Rangitoto (~600 years ago), comparison with lifespans of analogue volcanic fields and the presence of a mantle anomaly at depths of about 70 – 90 km beneath Auckland that has been interpreted as a zone of partial melting (Horspool, Savage & Bannister 2006) all suggest the field will erupt again (Lindsay 2010). Critical infrastructure including road transportation in the city may be affected by many volcanic hazards from both future eruptions in the AVF and volcanic ash from eruptions at any of the large andesitic to rhyolitic volcanic centres located >190 km away in the central North Island (Auckland CDEM 2015; Lindsay & Peace 2005; Steele et al. 2009) (Figure 1a).

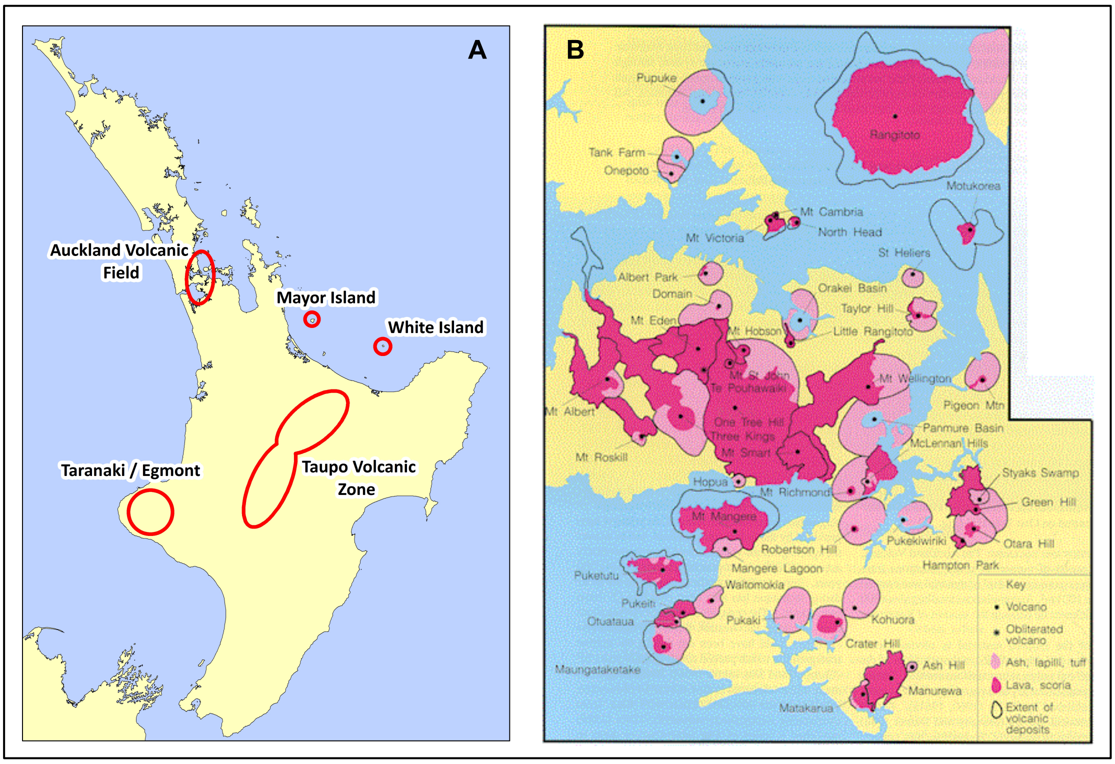

Figure 1. Potential sources of volcanic ash in Auckland including (a) volcanoes in the central North Island of New Zealand and Auckland Volcanic Field (AVF), (b) the AVF showing historic erupted material (Kermode 1992). Note that a new eruption in the AVF will likely occur from a new vent location anywhere within the approximate extent shown on the map.

3. METHODOLOGY

3.1 Skid Resistance

Skid resistance (i.e. the cumulative effects of water, snow, ice, other contaminants and the surface texture on the traction produced by the wheels of a vehicle) is a fundamental component of road safety and should be managed so that it is adequate (Dookeeram et al. 2014). It is essentially a measure of the Coefficient of Friction (CoF) obtained under standardised conditions in which the many variables are controlled so that the effects of surface characteristics can be isolated (Wilson & Chan 2013). We test the skid resistance on road surfaces using the British Pendulum Tester (BPT) (Figure 2), a standard instrument used by road engineers for surface friction testing since its development in the 1950s (Wilson 2006), and still used in many countries, particularly at problematic road sites. Despite the widespread and frequent use of the BPT by road engineers, we are unaware of other studies that have utilised the instrument on ash-covered surfaces.

The test procedure for the BPT is standardised in the ASTM E303 (2013) method. It is a dynamic pendulum impact type test, based on the energy loss occurring when a rubber slider edge is propelled across the test surface. Since the BPT is designed to test the skid resistance of extensive surfaces in-situ, care was taken to ensure that the instrument was stable before conducting our testing in the laboratory environment. We focus our testing on Stone Mastic Asphalt (SMA) concrete, a common surface on the Auckland State Highway network in New Zealand (Boyle 2005), in the form of slabs constructed by the Road Science Laboratory in Tauranga, New Zealand. The skid resistance of line-painted asphalt concrete was also tested using the BPT, after the slabs were machine painted by Downer Group (using a Damar Bead Lock Oil Based Paint containing 63% solids) in four forms (either 1 or 4 applications, with or without retroreflective glass beads).

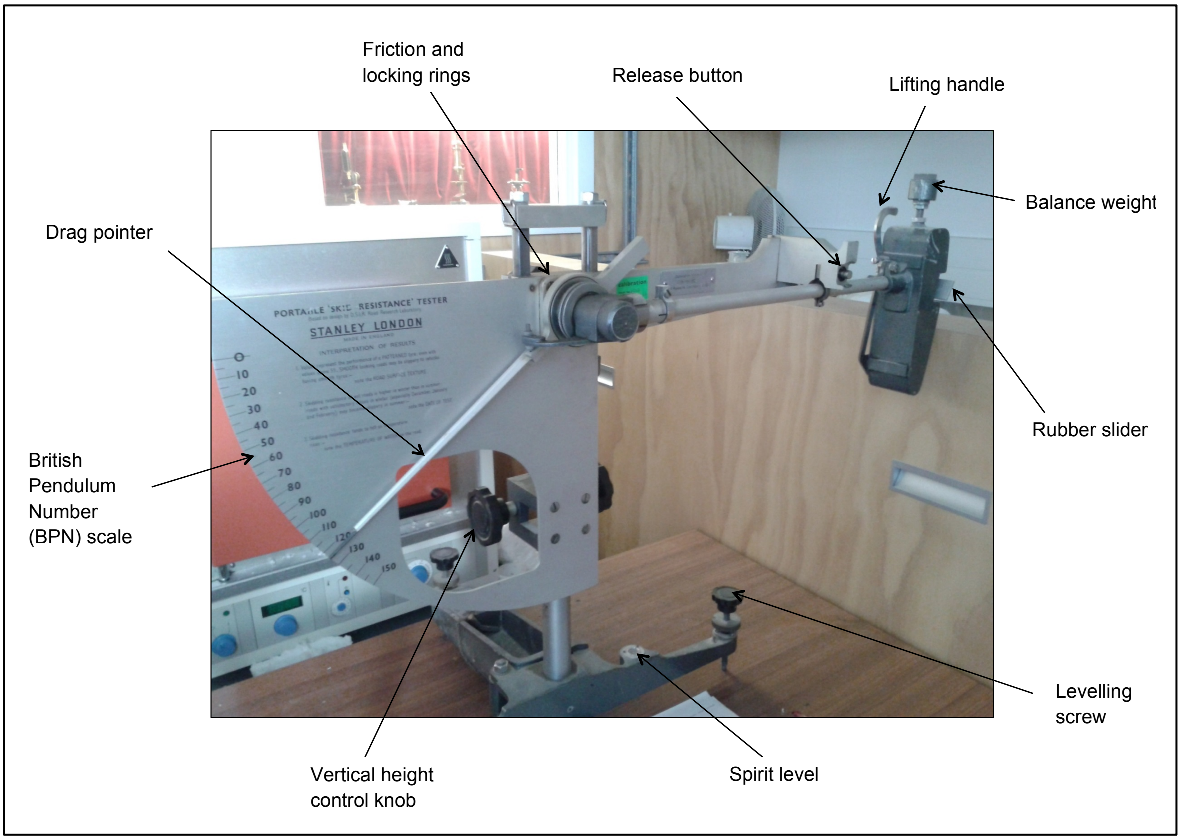

Figure 2. British Pendulum Tester (BPT) used for surface friction testing.

Three volcanic ash types (hard basalt, scoriaceous basalt and pumiceous rhyolite), sourced from different locations in New Zealand, were used in this study to investigate the effects of hardness and mineral components. Both dry and wet ash conditions were investigated for each type with the majority of ash sieved to 1000 μm but some sieved to 106 μm to also study the influence of particle size. Some ash was dosed with fluid from Ruapehu and White Island crater lakes in order to examine the effects of soluble components, which typically adhere to fresh volcanic ash, on skid resistance.

We adopted the same technique as used by the New Zealand Transport Agency (NZTA) (TNZ 2003), whereby for each test surface area, results of a minimum of five successive swings which do not differ by more than three British Pendulum Numbers (BPNs) are recorded. When analysing surfaces covered by ash, any ash that was displaced by the pendulum movement between each swing was replenished with new ash and re-wetted if applicable. The mean of the five BPNs was calculated to give a value representing skid resistance (i.e. the Skid Resistance Value (SRV)). The tests were conducted on every side of each slab to retrieve four SRVs for each condition, which were later averaged.

3.2 Road Marking Coverage

Road marking coverage by volcanic ash is of concern as markings typically provide much of the visual information needed by a driver to navigate roads safely (Gibbons, Hankey & Pashaj 2004). Coverage can lead to driver disorientation (Durand et al. 2001; Wilson et al. 2012a; USGS 2013) and cascading effects on vehicle movement across the road network, such as diminished flow capacity and an increase in traffic accidents (Wolshon 2009). Indeed, the Australian Automobile Association estimate that if 'average standard' road marking is maintained, the percentage of crash rates are reduced by between 10 and 40%, depending on the crash type (Carnaby 2005).

We adopt a method to replicate volcanic ash deposition on road surfaces in the VAT Lab by using the same SMA slabs painted with two thicknesses of line paint as described in section 3.1. The slabs were placed directly beneath an ash delivery system (Figure 3) to investigate thresholds for when road markings become obscured by ash. Samples included ash of three types; one of dark colouration (basalt), one of intermediate colouration (andesite), and one of light colouration (rhyolite), with three modal particle size distributions; fine (34-45 μm), intermediate (200-260 μm), and coarse (600-700 μm). Each sample was deposited onto the surface separately to provide means of contrast and particle size comparisons. Ash depths, measured from the surface of the asphalt concrete aggregate and within the aggregate voids using a caliper, and area density, calculated from the weight of ash in petri dishes, were recorded as the ash accumulated.

A series of digital images were taken in conjunction with the ash measurements using a camera mounted on a tripod 1.5 m horizontally and 1.08 m vertically away from the slab (Figure 3), 1.08 m being the typical height of a driver's eye above the road (Fambro, Fitzpatrick & Rodger 1997). Each image file was opened using Ilastik version 0.5.12 software (Sommer et al. 2011) and one class created for the white paint, and another class for ash or asphalt. After pixel segmentation, Adobe Photoshop version CS6 was used to ensure that each image was cropped to the same dimensions and the number of pixels for the ash/asphalt was calculated by subtracting the number for the white paint from the total pixel count in order to determine the percentage of visible white road markings throughout the experiment.

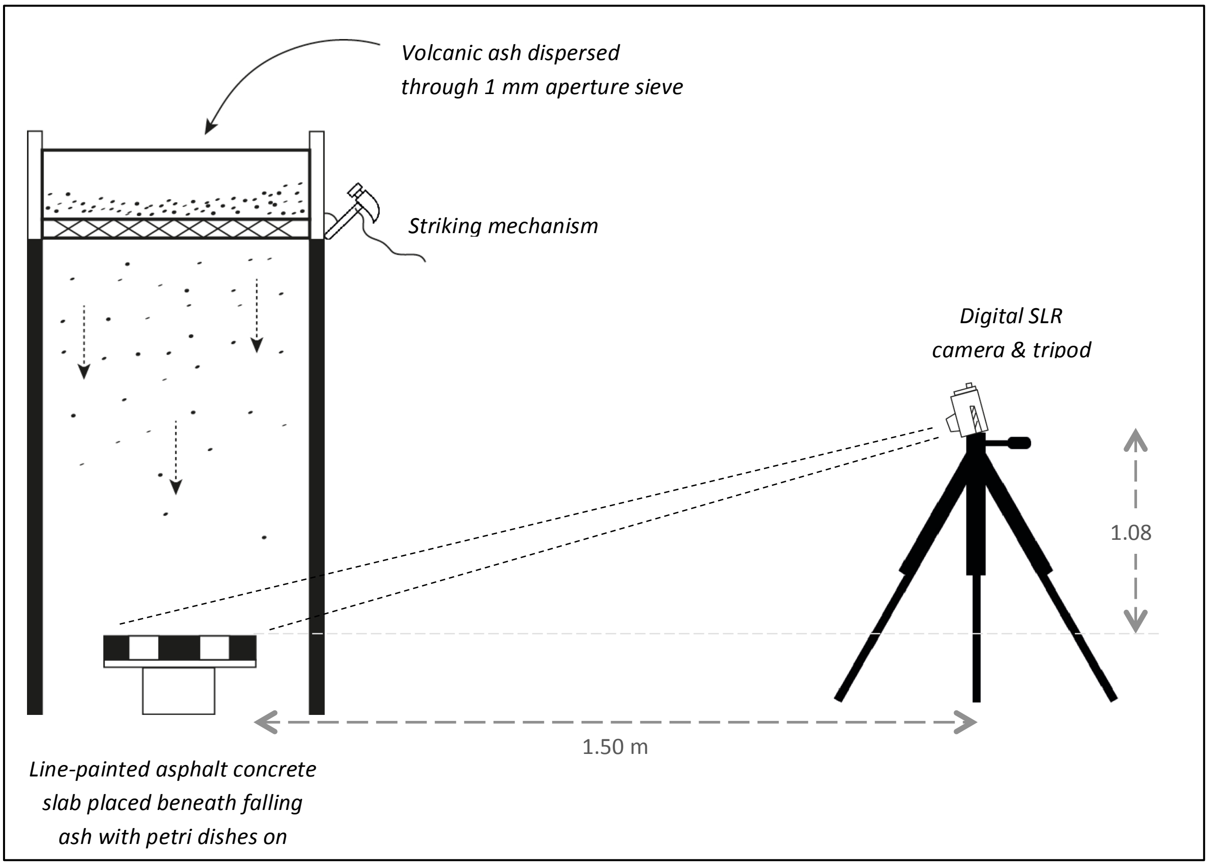

Figure 3. Experimental set-up for road marking coverage experiments.

3.3 Visual Range

Particles and gases interact with light to affect visibility and the interactions consist of light absorption and light scattering. The amount of light redirected from its original path is referred to as the total extinction coefficient (b_{ext}). Light scattering by particles is the dominant cause of reduced visibility in most areas because particles scatter light more efficiently than gases (van de Hulst 1957; White 1990; Hyslop 2009). Once b_{ext} is determined, the corresponding Visual Range (VR), which is often used to quantify visibility, can be calculated:

$$VR = 3.912 / (b_{ext} + 0.01) \quad \textbf{(1)}$$

Where the value of the numerator is constant and 0.01 is the Rayleigh coefficient corresponding to a "pristine" environment used to normalise the estimation (Barsotti et al. 2010).

VR is defined as the longest distance that a large, black object can be seen against the sky at the horizon with the unaided eye (Hyslop 2009). VR and b_{ext} are inversely related by the Koschmieder equation.

We investigate the VR through airborne volcanic ash using a set-up incorporating a Dual Pass Opacity Meter (Dynoptic DSL-460 MkII), and a Solid Aerosol Generator (Topas SAG

410) which replicates precise and consistent ash flow rates in a purpose-built enclosed cylindrical container (Figure 4). The opacity meter was calibrated to measure and record b_{ext} so that VRs could be calculated using equation 1.

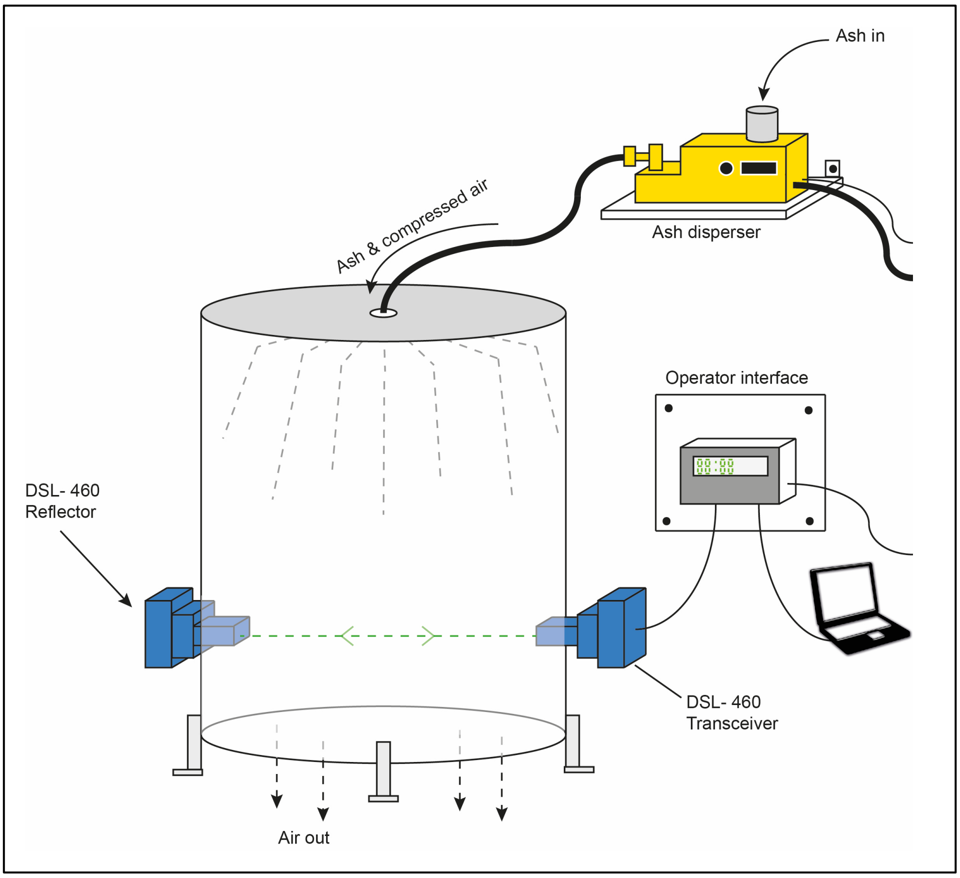

Figure 4. Experimental set-up to investigate visual range in airborne volcanic ash.

Experiments to calculate the visual range in different airborne concentrations of volcanic ash were ongoing during the write-up of this paper. As with the road marking coverage experiment (section 3.2), three types of ash of different colouration will be used in this study. A range of particle sizes (with mode diameters between ~10 μm and ~100 μm) will be incorporated in order to investigate the effect of particle size on visual range.

4. RESULTS

4.1 Skid Resistance

Mean Skid Resistance Values (SRVs) and the corresponding Coefficients of Friction (CoFs) for the non-contaminated SMA concrete (new and cleaned) and the the SMA concrete covered by three samples sieved to 1000 μm are shown in Figure 5. Our results confirm suggestions from anecdotal observations that skid resistance is reduced following unconsolidated ash accumulation. They also reveal that reduced SRVs are particularly pronounced under dry conditions for a 1 mm thick ash layer on SMA concrete. Mean SRVs for all 1 mm thick ash types fall below the typical minimum recommended SRV for difficult road sites (i.e., an SRV of 65). Wet 1 mm ash-covered surfaces are not necessarily more slippery than dry 1 mm ash-covered surfaces and the wet surfaces covered in 1 mm thick ash are only slightly more slippery than the wet asphalt without ash contamination.

Different trends are observed for SMA concrete covered by ash >1 mm thick. The hard basalt has similar SRVs to the 1 mm thick layer but the scoriaceous basalt and pumiceous rhyolite have greater SRVs than those for 1 mm of ash, suggesting that these ash types are perhaps less slippery when thicker. We note that the pendulum arm may be slowed upon initial impact with the thicker deposits, producing higher than true representative SRVs. However, the comparatively low SRVs for the 5 mm thick hard basaltic sample suggest that other ash characteristics are also important.

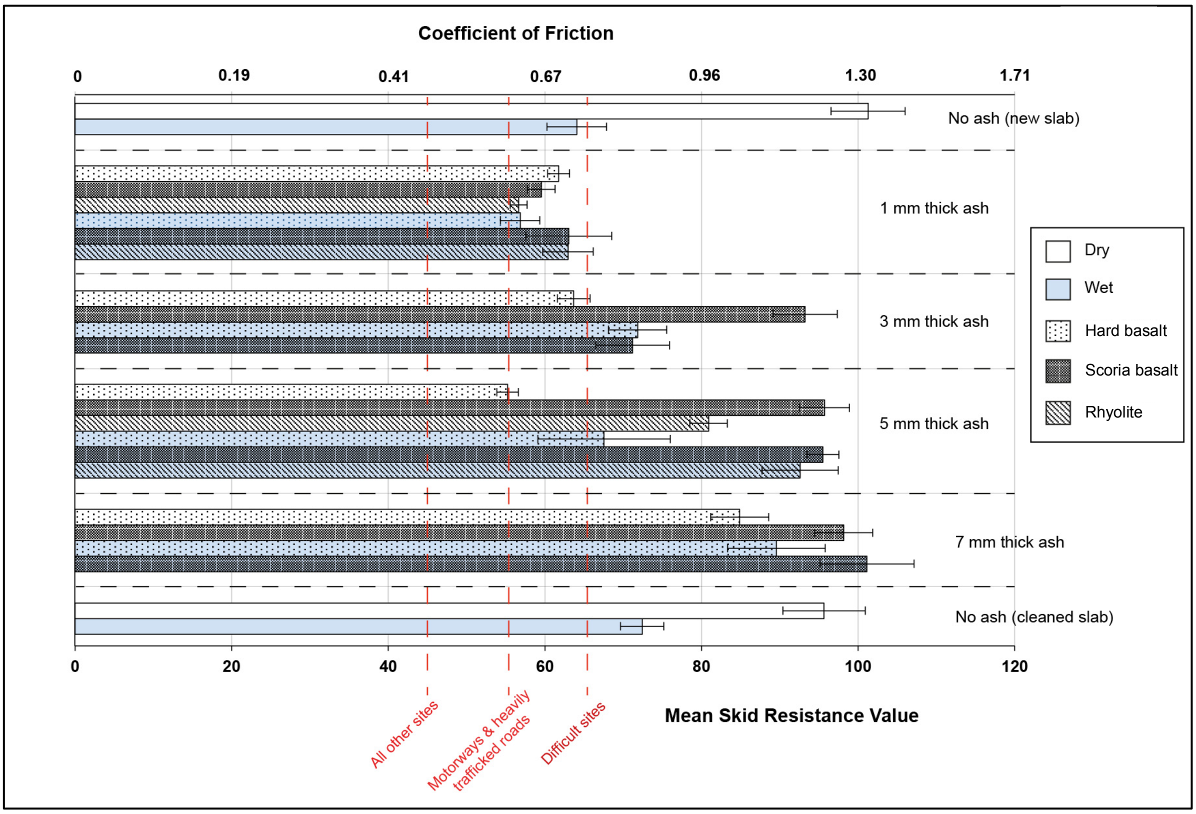

Figure 5. Mean SRVs and CoFs for the non-contaminated SMA and SMA covered in the three ash types sieved to 1000 μm. Wet and dry samples at 1, 3, 5 and 7 mm thicknesses are shown although limitations in the quantity of rhyolite meant that testing was only conducted at 1 and 5 mm thickness for this ash type. The error bars represent the standard deviation for each data set. Also displayed (as red dashed lines) are the minimum recommended SRVs for different road network sites (British Pendulum Manual 2000; Asi 2007; Impact 2010).

SRVs for the scoriaceous basalt containing adhered soluble components (i.e. the samples dosed with crater lake fluid) were generally less than those that were not dosed. Furthermore, as the degree of soluble components was increased, the SRVs decreased. However, no change was evident for the hard basaltic samples, perhaps due to the highly crystalline properties of this ash type reducing soluble component adherence.

Mean SRVs for the fine-grained ash samples were slightly higher than those for the coarse-grained ash of the same type when at 1 mm thickness, with mean values for both wet and dry samples above the minimum recommended SRVs for difficult sites. We suggest that this is due to the finer particles being more easily mobilised and displaced at the tyre-asphalt concrete interface at such ash depths, allowing improved contact between the tyre and road surface.

The mean SRVs on wet line-painted asphalt concrete surfaces with no retroreflective beads and no ash were the lowest of all our results (SRVs of 40-46 when wet). The addition of glass beads does increase SRVs (by around 5), although values are still relatively low. SRVs for 'clean' and dry line-painted asphalt surfaces are very high, but as with non-painted surfaces, the addition of a 1 mm ash layer decreases SRVs substantially. Conversely, the SRVs for wet asphalt concrete increase with a 1 mm ash layer to similar levels as for dry conditions. With a thicker (5 mm) ash layer on top of line-painted surfaces, SRVs increase.

4.2 Road Marking Coverage

Following initial ash dispersal events, the percentage of pixels representing white road marking paint was found to decrease substantially, suggesting that only very small surface depths are required for an impact on road marking visibility. Indeed, ≤8% of pixels for white paint (taken to be the threshold when it would be difficult for drivers to observe markings) without retroreflective beads was evident at area densities of 35-80 g m^{-2} for fine-grained ash. Although measurements of thickness proved difficult at such low accumulations, these area densities were estimated to correspond to depths of just ~0.1 mm measured from the surface of the asphalt concrete aggregate. Ash particle size distribution is likely the most influential characteristic for marking coverage at small depths and a mass of fine particles is much more effective at covering a surface than the same mass of coarse particles.

Multiple paint layers (assuming little wear) and paint that incorporates retroreflective glass beads make markings more difficult to distinguish when ash accumulates. Road markings covered by light-coloured ash of the same thickness as dark-coloured ash are also more difficult to distinguish due to low contrast (Figure 6). We also note that contrast requirements are greater the farther the object is from the driver (Gibbons, Hankey & Pashaj 2004). Therefore a driver's ability to see road markings with distance may be also be hindered by light-coloured ash more than ash of dark colouration. These findings especially highlight the susceptibility of road markings being covered in distal areas from volcanic vents where fine-grained and light-coloured ash is more likely.

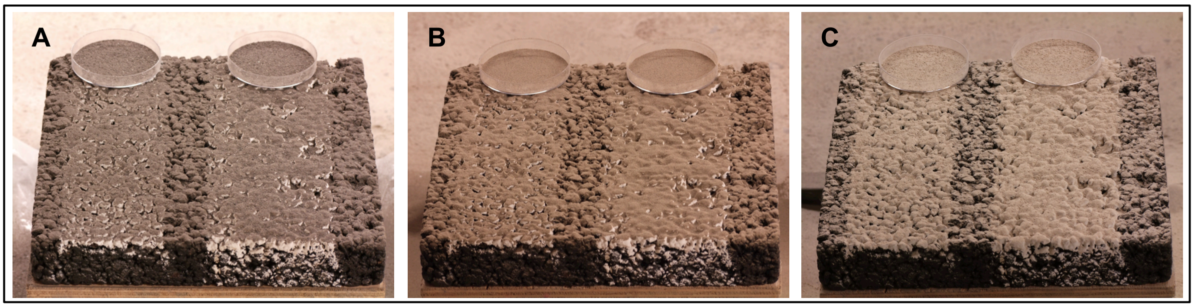

Figure 6. Road markings containing no retroreflective beads in the paint mix when ≤8% of line paint was visible for (a) basaltic, (b) andesitic, and (c) rhyolitic, ash of 200-260 µm modal particle size distributions. This corresponds to mean thicknesses on the surface of the asphalt aggregate of 0.55, 0.35 and 0.30 mm respectively.

We highlight the importance of outlining the specifics for depth type measured on road surfaces for ash accumulations less than ~10 mm. Depths within the asphalt aggregate voids were found to be over five times greater than those measured from the surface of the aggregate in some cases.

4.3 Visual Range

Preliminary results for the visual range experiments are for the basaltic ash sieved to 212 µm (with a particle size range of 1 – 280 µm and mode size of 105 µm) and dispersed into the cylindrical container at a flow rate of 69 g h^{-1} (Figure 7a) and 137 g h^{-1} (Figure 7b). Such characteristics represent approximately the mean particle size that can be expected from

Auckland Volcanic Field eruptions when at locations of ~4-11 km from a vent (Hopkins pers comm, 2014), and likely lie towards the lower end of ash settling rates that can be expected based on data from historical eruptions worldwide.

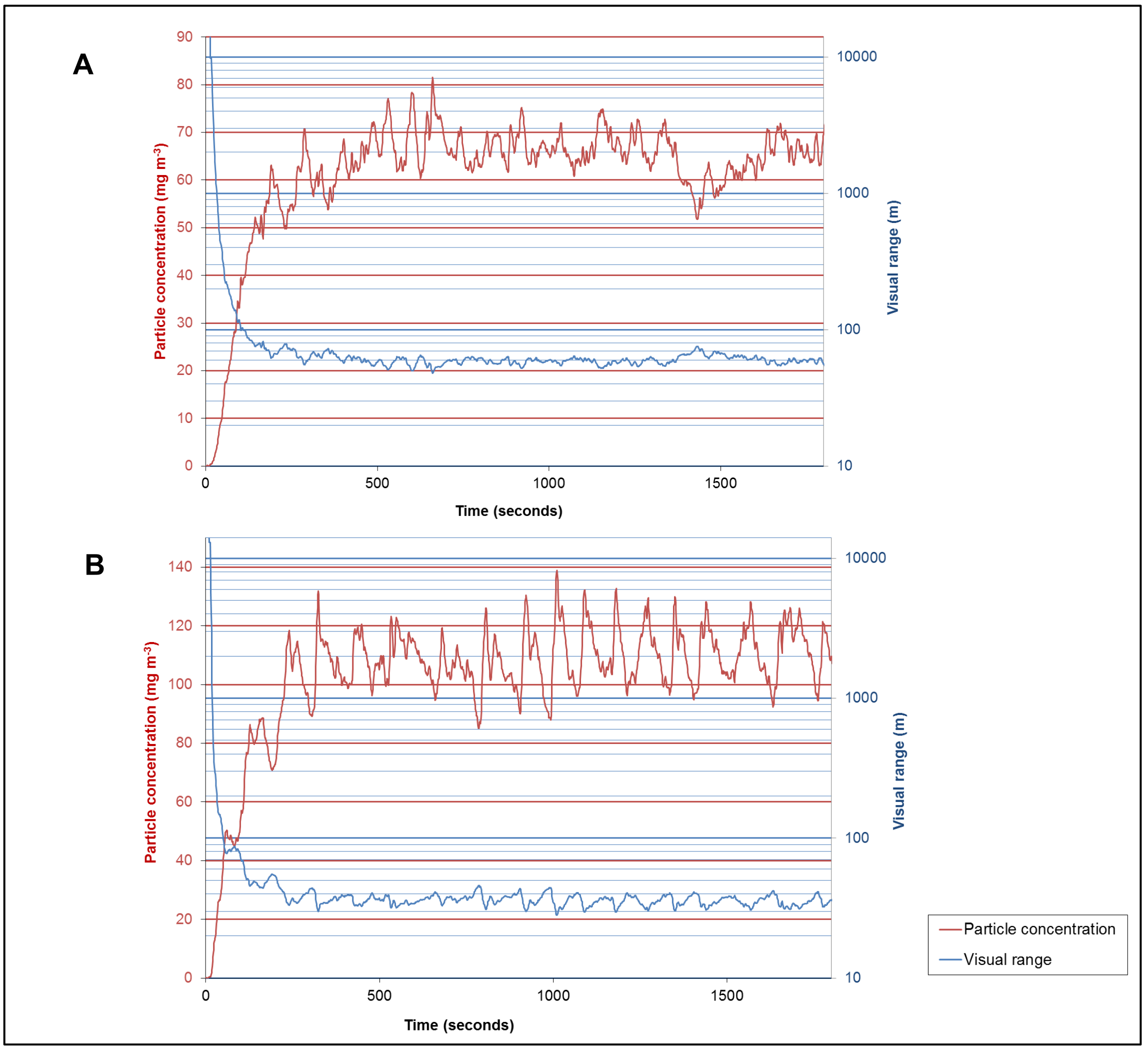

Figure 7. Visual range and particle concentration with ash sieved to 212 μm dispersed at (a) a flow rate of 69 g h^{-1} and (b) a flow rate of 137 g h^{-1}.

The visual range (calculated using equation 1) was found to decrease over around 300 seconds for both tests, albeit at a decreasing rate, reflecting the increase in airborne particle concentration. After this time, equilibrium between ash settling rate and flow rate (into the container) appears to have been reached. After 300 seconds at the lower flow rate, following dispersion of 5.8 grams of ash into the container, a particle concentration of around 65 mg m^{-3} and corresponding visual range of ~60 m occurred. At the higher flow rate, following dispersion of 11.4 grams of ash into the container, a particle concentration of around 110 mg m^{-3} and corresponding visual range of ~35 m occurred.

In previous studies to determine how drivers react when driving in varying levels of fog using a driver-simulation method (Brooks et al. 2011), a visual range of 18 m resulted in participants decreasing their average speed by over 5 km h^{-1} (from 88.6 km h^{-1}). However, it was calculated that drivers would be incapable of stopping to avoid obstacles in the roadway at such speeds, a situation that corresponds to what has been recorded on actual roads in inclement weather (Edwards 1999). Lane-keeping ability was reduced when fog resulted in visual ranges <30 m (Brooks et al. 2011). Such visual ranges and associated disruption are not anticipated for the same conditions as in our initial tests. However, it seems probable that they would occur at the mid-to-large range of ash settling rates that can be expected in Auckland with additional impacts on road safety including covered road markings and reduced skid resistance. Further testing will confirm the specifics.

5. DISCUSSION & CONCLUSIONS

5.1 Road transport resilience

The experiments and analysis demonstrate that very low quantities of volcanic ash (~0.1-1.0 mm surface depths) have the potential to cause substantial impacts to road transportation. It also appears likely that airborne ash can cause disruption at relatively high concentrations. Many ash characteristics are important to consider, not just the depth of ash. For example, the largest change in skid resistance for surfaces that become covered by ash occurs during dry conditions with ash type having a large influence on SRVs as the depth of deposits increases (i.e. thicker layers of hard basalt were found to be more slippery than scoriaceous ash at the same depth). Ash of low crystallinity containing a high degree of soluble components (i.e. replicating fresh deposits) was found to be more slippery than ash which had not been dosed, and road markings covered by fine-grained ash of the same thickness as coarse-grained ash are much more difficult to distinguish.

Based on findings so far, we make the following preliminary recommendations to increase road safety with volcanic ash exposure of ≤ 5 mm depth, therefore helping to increase the resilience of road transportation networks following eruptions:

- During initial ash fall, vehicle speed (or advisory speed) should immediately be reduced to levels below those when driving in very wet conditions on that road, whether the surface is wet or dry. Wet ash is not necessarily more slippery than dry ash, at least initially.
- Fresh ash generally contains more soluble components, which results in lower skid resistance values than for leached ash. Therefore, it is important to advise motorists promptly of any restrictions.
- Particular caution should be taken on dry surfaces that become covered by coarse-grained ash as skid resistance will reduce substantially from what occurs on dry non-contaminated surfaces. The slipperiness of dry surfaces with such contamination may not be expected by motorists.
- Road markings may be hidden from view with as little as 0.1 mm of ash if fine-grained, impacting road safety through lack of visual guidance of road features. Visual impairment of markings will be particularly problematic during rhyolitic ashfall due to lower visual contrast.
- Areas of road that are line-painted and covered in ash are also especially slippery. Motorcyclists and cyclists in particular should take extreme care.
- Visibility from direct ashfall will decrease quickly and likely fall to the lowest level after around 5 minutes of it arriving (assuming a consistent ashfall rate). Extreme caution should be taken as it may be difficult to avoid stopped vehicles and other obstacles, and lane-keeping ability may be reduced.

Our studies also allow thresholds and recommendations associated with road cleaning to be determined, which will improve road safety and network functionality during ashfall:

- Road cleaning should be conducted at or before ash area densities of 30-45 g m^{-2} for fine-grained ash of all types, 100-250 g m^{-2} for ash of intermediate size, and 1,000-1,500 g m^{-2} for coarse-grained andesite or basalt.

- Brushing alone will not restore surfaces to their original condition in terms of skid resistance:
    - If surfaces are dry and contaminated with ash, air blasting combined with suction and capture of loosened ash, is an effective way to remove ash from surface voids and restore skid resistance to near-original levels.
    - If surfaces are wet, a combination of water spraying and brushing and/or air blasting (with suction and ash capture) is an effective way to remove most ash and restore surface skid resistance.

Ash re-suspension and subsequent secondary deposition should be carefully considered prior to cleaning. Extensive (and often expensive) cleaning efforts may be wasted if substantial ash is still present in the environment and continues to be deposited onto road surfaces.

5.2 Modelling disruption and recovery in Auckland

Our results are informing models of critical infrastructure disruption and recovery in central Auckland following hypothetical eruptive scenarios in the AVF. Modelling includes the recently extended Mt. Ruaumoko volcanic eruption scenario (Deligne et al. 2015), developed as part of the Economics of Resilient Infrastructure (ERI) research programme, a four-year project funded by the New Zealand government. Mt. Ruaumoko is a hypothetical volcano that first emerged during ‘Exercise Ruaumoko’ in 2007/08, the largest Civil Defence and Emergency Management exercise in New Zealand, which tested national arrangements for responding to a major disaster in Auckland. The extended scenario includes a sequence of time-series maps that convey infrastructure outages in terms of the change in ‘level of service’ experienced by the end-user during the course of the eruption. An example of road transportation ‘level of service’ experienced during this scenario is shown in Figure 8.

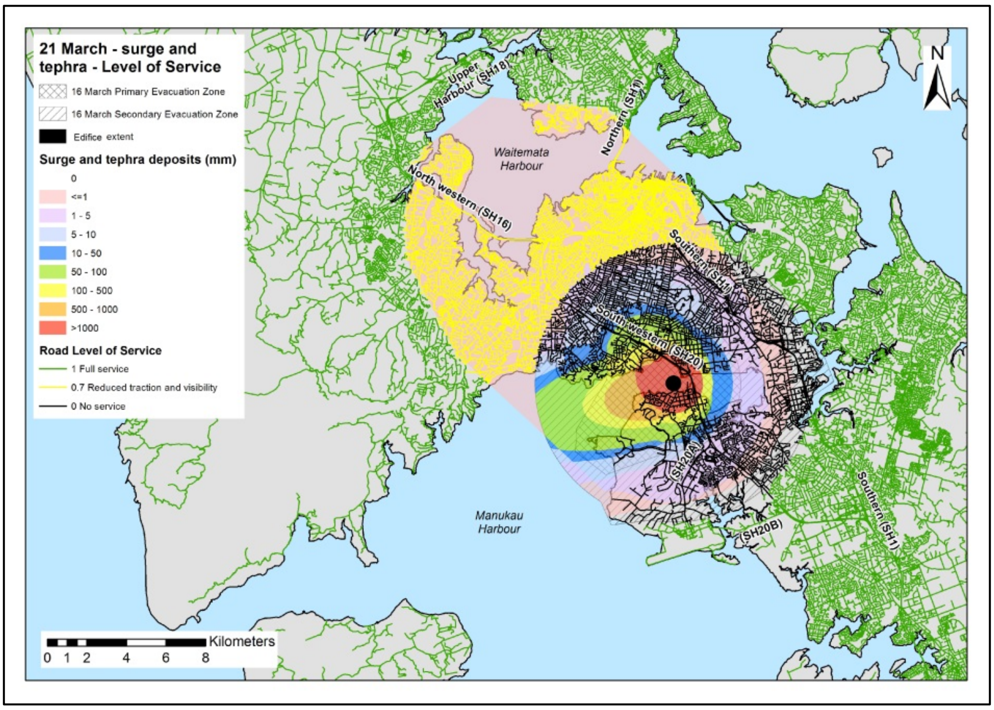

Figure 8. Level of service for road transportation experienced on 21 March during the hypothetical Mt. Ruaumoko eruption in the AVF (Deligne et al. 2015).

The anticipated level of service on central Auckland roads affected by ash fall deposits ≤ 1 mm is 0.7 (coloured in yellow on Figure 8), 1 conveying the ‘typical’ full service level and 0 describing ‘no service’. This reduced level of service for roads was based on anectodal evidence from previous eruptions worldwide, discussions with road transportation managers in Auckland, and the empirical evidence determined by laboratory studies described in this paper, which suggested that both skid resistance and visibility (of road markings and through airborne ash) will be reduced at such depths. Further work will analyse impacts to critical infrastructure including road transportation across the full extent of the AVF using a grid-based probabilistic method and incorporate a range of possible eruption styles and associated volcanic hazard ‘rules’. This will enable the identification of road transport disruption ‘hotspots’ in Auckland, allowing further improvements in risk management for volcanic eruptions and an increase in overall transport system resilience.

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We would like to highlight that much of the research outlined in this conference paper is intended for publication in a more detailed format within peer-reviewed academic journals.