Transportation impact assessment following a potential Alpine Fault earthquake in New Zealand

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Abstract:

The Alpine fault, one of the major fault systems in New Zealand, extends over 600km in the South Island. There is a high probability of a rupture in the next 50 years, meaning that the next large earthquake on the Alpine Fault is likely to occur within our, or our children's, lifetime. This is predicted to result in severe damage to the built environment, especially to infrastructure. To estimate the performance of the road network impacted by an Alpine Fault Magnitude 8 earthquake scenario, this research developed a generalizable methodology to simulate post-disaster transportation impacts on a large regional road network. This included the base model development and model calibration, as well as validation in a post-disaster situation. Post-disaster corridor and district trip analyses were undertaken using the outputs of the dynamic assignment, including mean travel time, total travel time, total travelled distance, and flow. The result of corridor analysis shows the significant increase in flow and total travel time on SH1 between Marlborough and SH7, and SH6 connecting Nelson to Marlborough one day and one week after the impact. The trip analysis of one day, one week, six months, and beyond six months after the earthquake indicates that around 2.02%, 1.16%, 0.39%, and 0.13% of total trips, respectively, cannot occur due to accessibility issues. Almost all of the inter-district trips from the three main impacted districts, namely Buller, Westland, and Grey, would be cancelled for at least one week after the earthquake with the impact on operational performance still ongoing. Trips that can occur typically face a significant increase in travelled distance and, consequently, travel time. The outputs from this model will provide emergency response and transportation organisations with critical information regarding the performance of the network following an Alpine Fault Magnitude 8 earthquake.

Keywords: Transportation Resilience, Alpine Fault Earthquake, Mesoscopic Simulation, Post-Disaster Modelling, Operational Performance.

1. Introduction

The impact of natural hazards on communities, from a structural, environmental, social, and economic perspective, are increasing worldwide. Average economic losses from the five most devastating disasters each year between 2000 and 2014 have increased from US$250 billion to US$300 billion (UNISDR, 2015). In 2011, earthquakes alone resulted in an economic impact of US$240 billion, the most devastating year since 2000. Since 2010, three major earthquakes have occurred in New Zealand (NZ), all in the South Island, causing 184 deaths and an estimated US$28.450 billion in damage (EM-DAT, 2017). The 2010 and 2011 Canterbury earthquakes were the most devastating, resulting in 182 fatalities and estimated damage costs of $15 billion, about 8% of NZ GDP (NZTreasury, 2011), including approximately $46 million damage to the road network (Eidinger and Tang, 2012). The 2016 Kaikoura earthquake affected a number of industries in the Kaikoura and Hurunui districts, especially tourism and primary production (seafood and dairy) due to infrastructure disruption (NZTreasury, 2016). Damage costs were significant, around $1.5 to $2.0 billion (NZTreasury, 2016), and most of them were related to transportation infrastructure (road and rail).

Two of the most destructive earthquakes in the West Coast Region of the South Island include the 1929 Murchison Earthquake and the 1968 Inangahua Earthquake (Benn et al., 2002). However, if an Alpine fault earthquake was to occur then it could potentially be even more devastating. The Alpine fault is the longest active fault in NZ, measuring more than 600km long, with the largest average long term slip rate (Yetton, 2000). Berryman et al. (2014) reported the probability of occurrence of an Alpine Fault Magnitude 8 earthquake in the next 50 years as 30%, resulting in an estimated $10 billion in economic cost. Benn et al. (2002) reported a 65% probability of the Alpine fault rupture occurring in the next 50 years, and almost 85% probability in the next 100 years. Therefore, rupture of the Alpine fault is almost inevitable, with severe damage predicted to the built environment, especially to infrastructure. Yetton (2000) reported that the rupture of the Alpine Fault might be felt in all districts of the South Island, causing serious damage to the West Coast Region (Westland and Buller), Canterbury, and Otago. A future Alpine Fault earthquake is, therefore, of real concern with the next large earthquake on the Alpine Fault likely to occur within our, or our children's, lifetime.

In response to this risk, the Alpine Fault Magnitude 8 (AF8) Project was established, funded through the Ministry of Civil Defence & Emergency Management's Resilience Fund. This is a three-year programme focussing on two workstreams, namely "response" which aims to develop the emergency response plan, and "risk" which is related to the hazard scenarios based on earthquake source and geomorphic components (Orchiston et al., 2016). As part of the AF8 Project, Orchiston et al. (2018) developed a multi-agency response plan to enhance societal resilience to a future earthquake. The potential geomorphic consequences including landslides, landslide damming, dam-break flooding, debris flows, river aggradation, liquefaction, and landslide-generated lake/fiord tsunami have been investigated by Robinson and Davies (2013). Although the physical impact of the AF8 has been studied in detail, there is a paucity of research in the literature assessing the operational performance of the road network following such an event. Only one study (Robinson et al., 2015) has estimated the operational performance of the road network post-disaster. The study was limited to the estimation of travel time variation between key South Island nodes (cities) using an Origin-Destination Cost Matrix in a Geographic Information System (GIS) for different time periods post-disaster. An Origin-Destination cost matrix analysis determines the least-cost paths on a network from multiple origins to multiple destinations.

Consequently, this paper aims to develop a methodology, including base model development, calibration and validation, to simulate post-disaster transportation impacts on a large regional road network. The methodology will be demonstrated using the road network for the South Island of New Zealand, however, it is equally applicable elsewhere using equivalent data from other countries or regions. The model will then be applied to evaluate the operational performance of the South Island road network following a potential Alpine Fault Magnitude 8 earthquake. The model uses a combination of simulation software and analytical methods to assess the operational performance. This will be evaluated for different time periods post-disaster, namely after one day, one week, one month, six months, and beyond six months. The proposed methodology to assess the transportation impacts on the road network is presented in the next section, followed by the developed scenarios. Operational performance of the network is then examined in the “corridor analysis” and “district trip analysis” sections. Finally, the results are discussed and conclusions presented.

2. Methodology

The impact of disasters on a road network can be assessed based on the physical impact and/or the operational impact. The physical impact examines the effect of disasters on different assets such as pavements, structures, bridges, and tunnels, which in turn can cause disruption on the network, completely or partially. Therefore, the travel behaviour of the users will vary, causing increased travel time and travel cost, or even unsatisfied demand (El-Rashidy and Grant-Muller, 2014, Jenelius et al., 2006). This is referred to as the operational impact of a disaster. Risk, vulnerability, reliability, robustness, flexibility, survivability, and resilience are the most common performance metrics or concepts applied in the literature to evaluate the impact of disasters on transportation networks (Faturechi and Miller-Hooks, 2014).

To assess the operational impact of the network, three approaches have been reported in the literature, namely: conceptual, analytical and a combination of analytical and simulation. The conceptual approach estimates the performance of the network using questionnaires and qualitative methods (Mason and Brabhaharan, 2016, Wang, 2015, Hughes and Healy, 2014, Tamvakis and Xenidis, 2012, Brabhaharan et al., 2006). The analytical approach utilises mathematical methods to assess the performance of the network (Zhang and Wang, 2016, Pokharel and Ieda, 2016, Zhang et al., 2015, Miller-Hooks et al., 2012, Chen et al., 2012, Taylor et al., 2006, Jenelius et al., 2006, Murray-Tuite and Mahmassani, 2004). The main drawback of the analytical approach, especially for large-scale networks, is the fact that they are computationally intensive (Luathep et al., 2011). The latter approach, used in this study, is a combination of analytical and simulation. It utilises simulation software to estimate the required traffic parameters, then evaluates the performance of the network using analytical methods and extracted traffic parameters.

The simulation software chosen to develop the model was Aimsun Next 8.3.0, and it was run using an Intel® Xeon® Gold 6134 CPU @ 3.20GHz 3.19GHz (2 processors) with 128GB memory. Generally, three sources of data are required to develop a traffic simulation model. The first is used to build the model, the second is used to calibrate the model, and the third is used to validate the model (TRB, 2010). Each of these steps will be discussed in turn in the following sections, followed by details of how to set up the model for a post-disaster situation.

2.1 Base Model Development

Data required to build the base model include supply data and demand data. A flowchart outlining the methodology for establishing the supply data and creating the travel demand is included in Figure 1.

Road Network

To build the network, the Open Street Map (OSM) file was imported into Aimsun directly. To check the accuracy of the OSM imported road network, the New Zealand road centreline GIS shapefile (LGNZ, 2017) was added as a layer to the model. Since the OSM file contains all categories of the road network, and this research aims to model only the main corridors in the South Island, unnecessary links were removed to simplify the network based on the NZTA’s One Network Road Classification (ONRC), Google Earth, and Google maps. Detectors were then located on the network model, to mirror the physical detectors on the road network, based on their geographic coordinates. Imported road features, such as speed and capacity, were amended using the NZ Economic Evaluation Manual (NZTA, 2016) and Google maps. A total of 622 detectors were located on the network at 311 locations providing excellent coverage of the main highways and corridors. After the static assignment was completed, the control plans for the signalised intersections on the network were created using static demand on each approach and turn. This was then applied to the dynamic assignment.

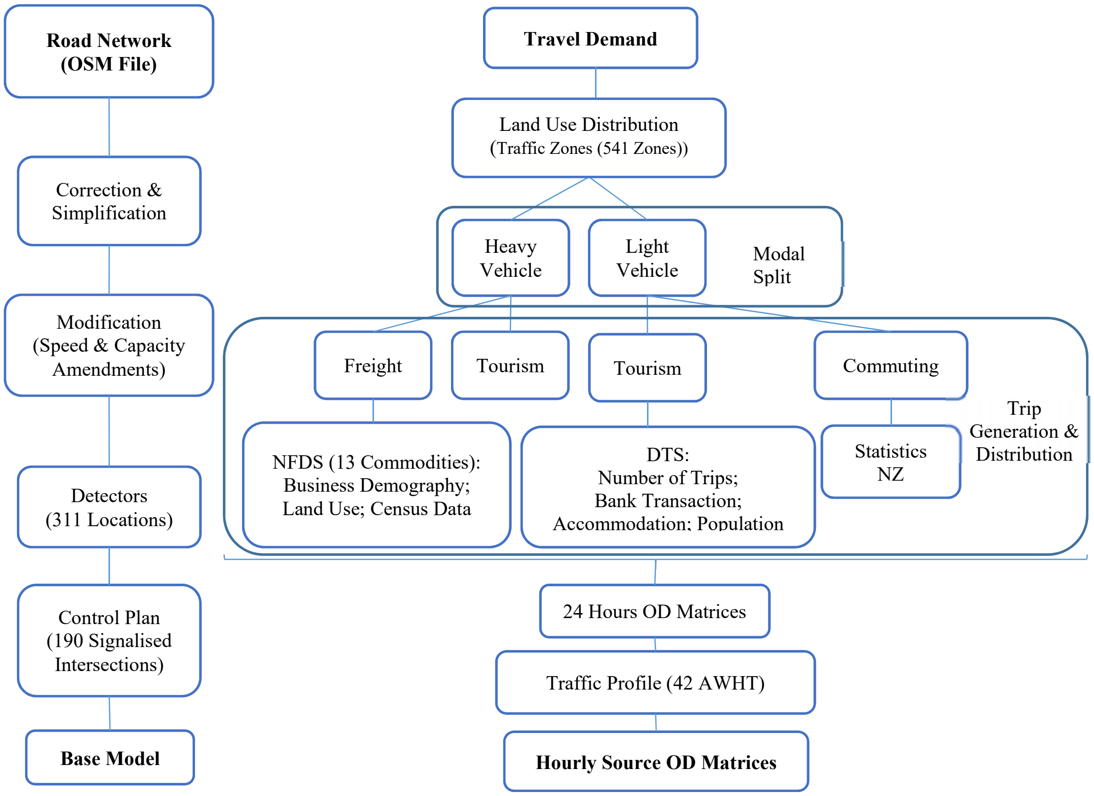

Figure 1: Methodology to Develop the Base Model

Travel Demand

Travel demand modelling is a critical part of transportation planning arising from the need to connect different land uses, such as residential to business, recreational, and educational, based on individual human behaviour influenced by several factors including “the size of the city, its urban density, its layout, the demographic and cultural properties of its population, economic conditions and the type and quality of the transport networks.” (Moran and Veysey, 2013). To estimate travel demand, knowledge of specific analytical parameters are required, such as destination attraction weight, mode choice, assignment methods, periods of travel, and representation of flow (Alexiadis, 2008).

The standard four-step method was applied to create the OD matrices consisting of Trip Generation, Trip Distribution, Modal Split, and Trip Assignment, with Modal Split being undertaken as the first step. Modal split aims to determine the type of mode used for each movement. Three main purposes were identified to cover the movements on the network: commuting, tourism, and freight. Commuting and tourism trips cover the light vehicle movements on the network, while freight produces heavy vehicle trips. Trip generation determines the number of trips produced at each traffic zone for each purpose. It is a function of land use, demographics and other socio-economic parameters (Moran and Veysey, 2013). Trip distribution indicates how the generated trips of each traffic zone are distributed to the other traffic zones. The process of allocating trip matrices to the network and choosing the best path based on travel impedance of the transportation network, including travel time, travel cost, and travel distance, is known as traffic assignment (Saw et al., 2015). Generally, trips can be assigned to the network statically (macroscopic models) or dynamically (mesoscopic or microscopic models). Given that trip assignment is part of the calibration process, it will be discussed in detail in the model calibration section.

A basic step in travel demand modelling is to select the appropriate traffic zones (centroid configuration) with regards to the land-use distribution, the scope of the network, availability of datasets, and trip purposes. They characterise the areas generating or attracting trips and should coincide with the Census Collector Districts (Moran and Veysey, 2013). Traffic zoning is the basis of traffic modelling and it is critical at this stage to get it right due to the difficulty of altering in the future. The census data is available in four levels including mesh blocks, area units, districts, and regions. Given the scope of this project, modelling inter-city trips on regional and main corridors, the unit areas were selected as the basis of the traffic zoning (centroid configuration). Area units or unit areas are non-administrative geographic areas and aggregations of meshblocks. They are approximately the size of suburbs with a median population size of 2,000 people. In urban areas they usually cover a population of 3,000-5,000 people (StatsNZ, 2018). This resulted in the South Island being divided into 541 traffic zones representing unit areas.

Commuter trips were determined from 2013 census data based on where people live and work. This data includes the number of commuters in and out of the unit area, the main means of travel and the employed population (StatsNZ, 2018). Private car and company car trips were summed up and used in the OD matrix.

The main source for tourism data is Statistics NZ (census data) and the Ministry of Business, Innovation and Employment (MBIE). There are two kinds of survey available for the tourism industry; the Domestic Travel Survey (DTS) and the International Visitor Survey (IVS). Two sets of information were utilised to find the OD matrix for domestic tourists; the number of trips (day, overnight and total) (StatsNZ, 2018) and trip distribution patterns based on bank transactions (MBIE, 2018). Trip distribution patterns between seven regions, as origins, and fourteen Regional Trip Organisations (RTOs), as destinations, were developed based on bank transactions recorded for the accommodation industry. To estimate the number of trips, the total number of trips for each RTO was applied to calculate the annual and daily number of trips for RTOs and Regions. The destination of each RTO and the number of accommodation outlets extracted from the Regional Tourism New Zealand website (RTO, 2018) were applied as an attraction weight. The population was also applied as a generation weight. Finally, the OD matrix of the tourism trips was created based on bank transactions for accommodation, the number of accommodation outlets, population, and the total number of tourism trips.

Heavy vehicle travel demand was created based on the "National Freight Demand Study (NFDS)" undertaken by the Ministry of Transport (MOT). Data, from 2012, for 19 different commodities for the South Island were extracted containing domestic, export, and import movements between five different regions, reported in million tonnes transported by road, railway, and coastal shipping. Total movements, in million tonnes, were then converted to the number of road trips based on the percent of road movements and the average payload of 10 tonnes (NFDS, 2014). Finally, the daily trips were calculated for each commodity between the five regions. Finally, all created OD matrices for HV movements were summed up in one OD matrix, ready to import to the network.

To create an hourly traffic release profile of the three matrices (commuter, tourism and heavy vehicle), the Average Weekday Hourly Traffic (AWHT) of 42 sites on the network were used. The hourly source OD matrices and the base model are the inputs of the calibration process, as will be detailed in the next section.

2.2 Model Calibration

The model was calibrated in two steps, the first step was to estimate the final travel demand matrices based on the three created source matrices using static assignment and matrix estimation methods, as shown in the Macroscopic Process box in Figure 2. In this process, the created hourly source matrices were assigned to the base model statically. The modelled traffic volume was checked against the real traffic count data, and the calibration criteria (NZTA (2014) were not met. The OD matrices, therefore, were adjusted until the criteria were met. Matrix estimation is a common calibration process applied to decrease the differentiation between observed and modelled count data. Three frequently used methods to estimate the demand matrix for a network include direct sample estimation, model estimation, and estimation from count data (Cascetta, 1984). The first one is based on different types of survey and interviews. The second method utilises a system of models to increase the accuracy of the estimated matrix by adding and correlating more variables (Cascetta, 1984). The last one, used in this study, aims to adjust the matrix based on the observed traffic count data on the network. Matrix estimation applying count data can be regarded as an inverse process of the traffic assignment (Bell and Iida, 1997). The traffic assignment utilises the OD matrix to calculate link flows using route choice models. The matrix estimation, however, utilises link flow (count data) to estimate the OD matrix using route choice models (TSS, 2017). The static OD adjustment process of Aimsun (TSS, 2017) was applied to adjust the source matrices and create the final OD matrices. The outputs of the macroscopic calibration are the adjusted OD matrices and static path assignments, which were applied to the dynamic assignment, as shown in the Mesoscopic Process box in Figure 2.

Two dynamic methods, Stochastic Route Choice (SRC) and Dynamic User Equilibrium (DUE), were assessed to determine which one best suited the project based on the scope and aim. Finally, the route choice parameters and centroid connections were altered to either increase the value of goodness-of-fit or decrease the virtual queue (vehicles waiting to enter the network) to improve the performance of the model. The output of this process is the calibrated base model at the mesoscopic level. Given that choosing an appropriate traffic assignment model, especially at the mesoscopic level, has a significant impact on the calibration process, the next section is devoted to the traffic assignment methods at the static and dynamic level.

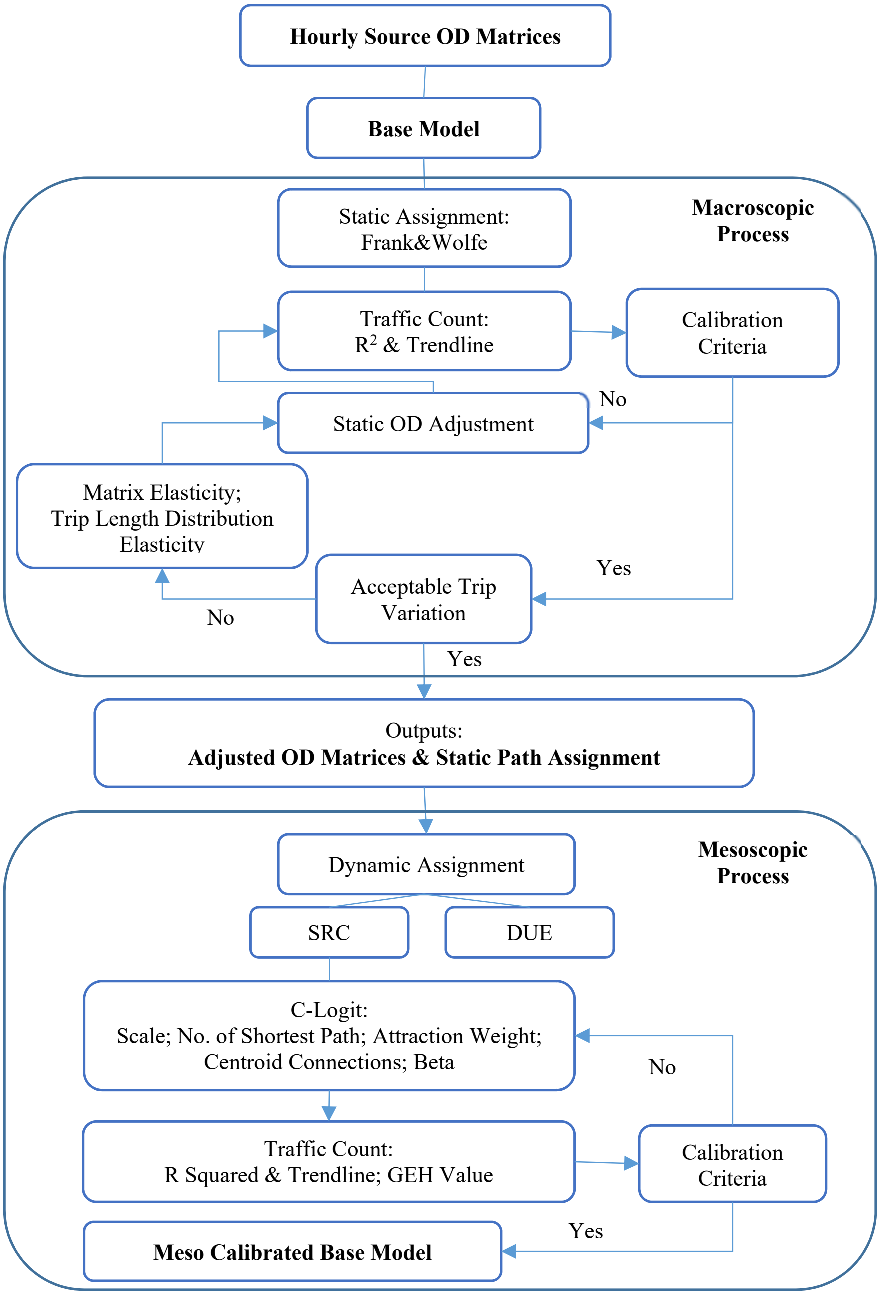

Figure 2: Flowchart of Calibration Process

2.2.1 Traffic Assignment Methods

Knowledge of critical parameters in the calibration process can improve efficiency and effectiveness. In a large network, it is advisable to adjust the global parameters to calibrate the whole network rather than local parameters. Key global parameters include the factors used in the traffic assignment process and the probability methods.

Static and dynamic traffic assignment models are explained in detail below, followed by the selection of the appropriate model for this study. As mentioned previously, trips can be assigned to the network statically (macroscopic models) or dynamically (mesoscopic or microscopic models). Macroscopic models are known as strategic models and are commonly used by transport planners to predict travel demand and travel patterns (Han et al., 2017).

Static Assignment

In a static assignment, a deterministic algorithm is applied to assign the trips to the network using trip volumes, speed, density, and flows on the links (TSS, 2017, TRB, 2010). As a result, static assignment cannot consider any traffic congestion and, generally, dynamic characteristics of the traffic on the network. TSS (2017) utilises five methods for static path assignment, all based on finding the shortest path and path percentage use. The five methods are: All or nothing assignment; Incremental Assignment; Frank and Wolfe Assignment; Method of Successive Averages (MSA) Assignment; and Stochastic Traffic Assignment. Apart from the stochastic assignment, the rest of the methods are based on deterministic methods. Due to the limitations of static assignment, including ignoring congestion and queues, neglecting car behaviour models (car-following and lane-changing methods), and lack of output data, it is generally only applied to strategic transportation planning such as travel demand modelling. Here, the macroscopic model is utilised to assign and adjust source matrices and estimate the final travel demand matrix. In this case, the travel demand is estimated based on business as usual conditions when the network is performing under user equilibrium conditions, therefore, the Frank & Wolfe method was selected for the macroscopic model.

The Frank and Wolfe assignment and MSA assignment are both based on the user equilibrium method, Wardrop's first principle: "the traveller time between a specified origin and destination on all used routes is equal and less than or equal to the travel time that would be experienced by a traveller on any unused route,". The MSA is a simpler and faster version of the Frank and Wolfe method which uses average flow from earlier iterations to find the new solution for the last iteration (Mirchandani et al., 2003). "The Frank and Wolfe algorithm is based on a shortest paths algorithm and an ad hoc implementation of a linear approximation algorithm," (TSS, 2017).

Dynamic Assignment

A detailed time-dependent dynamic traffic assignment (DTA) is required to examine the complexity of transportation systems. Among two main approaches to solve the DTA problem; namely the mathematical approach and simulation-based approach, the latter comprises two methods: route choice models and dynamic user equilibrium (DUE) (Casas et al., 2010). Route choice functions use different criteria in terms of travel time, distance, expected traffic conditions, and other parameters to model driver behaviour on the road (Barceló and Casas, 2006, Casas et al., 2010). Travel demand can be assigned to the network using four route choice options: Binominal (probability), Proportional (alpha-factor), Logit (scale factor), and C-Logit (scale factor, beta and gamma) (Casas et al., 2010). Since the aim of the project is to assess the performance of the network in case of emergencies, the network will not be in user equilibrium, and travel patterns and behaviour will change. Therefore, the network was calibrated using the stochastic route choice model, not DUE. Among the four mentioned methods, the Logit and C-Logit methods are applicable to large networks.

The multinomial logit model represents the probability of selecting the shortest path comparing measured (dis)utilities of a path to all other alternative paths (Barceló and Casas, 2006). The normal Logit function used to find the choice probability is expressed below:

$$P_k^i = \frac{e^{-\theta t_k^i}}{\sum_{l} e^{-\theta t_l^i}} = \frac{1}{1+\sum_{l^1 k} e^{-\theta(t_l^i - t_k^i)}} \tag{1}$$

Where $t_k{}^i$ is the travel time on path k of OD pair l and θ is a scale factor. The scale factor plays an important role in the calibration of the network. If the factor chosen is less than one, then many alternative routes will be utilised and, conversely, with a factor greater than one, very few routes will be selected (TSS, 2017). However, there is a tendency toward route oscillation with the instability creating a kind of 'flip-flop' process which results in a certain drawback in using the Logit model when there is a high degree of overlapping among alternative routes (Barceló and Casas, 2006).

The C-Logit model is implemented to decrease the impact of this drawback of the Logit model and is expressed as follows:

$$P_k = \frac{e^{\theta(v_k - CF_k)}}{\sum_{l \in k_i} e^{\theta(v_l - CF_l)}} \tag{2}$$

Where v_i is the perceived utility for an alternative path i, and θ is a scale factor. The term CF is known as the "commonality factor" addressing the degree of overlapping among paths. It is calculated as:

$$CF_k = \beta . \ln \sum_{l \in k_i} \left(\frac{L_{lk}}{L_l^{1/2} L_k^{1/2}} \right)^{\gamma} \tag{3}$$

The CF factor is assessed based on link costs and two-factor parameters β and γ, of which the first one has more impact on calibration. Larger values of β indicate more influence of overlapping on the route choice. Larger β values increase the influence of the CF factor on the choice probability rather than the (dis)utility (travel time) factor (v_i) (Barceló and Casas, 2006).

While the Logit and C-Logit methods are based on the Logit function, there is a drawback in the Logit method, especially in large networks with a high degree of overlapping paths. In New Zealand's South Island road network there are not many alternative routes between different traffic zones, especially between cities. In most cases, State Highways are the main routes connecting many traffic zones, which results in a high degree of overlapping on the network. As a result, the C-Logit method was selected to assign the trips and calibrate the network. Several critical global parameters including the number of shortest paths, scale, attractiveness weight, Beta, Gamma, and route choice percentage were altered to achieve the appropriate results. Running time for each mesoscopic scenario with 15 minutes costs cycle time (CCT) was around 25 to 36 hours. Because several runs were required to determine the values needed to calibrate the network, the costs cycle time was increased to one hour to reduce the run time to around 3 to 4 hours. After 19 different runs with CCT of an hour, the Stochastic Route Choice, C-Logit model with a scale of 3 and shortest path (K-SP) of 2 were selected as the final parameters for the calibrated network. For the last run, the finalised parameters brought forward from the CCT runs of an hour were loaded to the model with 15 minutes CCT and the model returned an acceptable R squared and hourly GEH results based on the NZTA (2014) criteria.

2.3 Model Validation

The 2016 Kaikoura earthquake, a 7.8 (Mw) magnitude event, provided a unique opportunity to validate the South Island road network model in a post-disaster environment, as reported in Aghababaei et al. (2020). While conventional network analysis methods are employed with a degree of uncertainty in travel demand behaviour in a post-disaster scenario (Khademi et al., 2015), the validation of the network using post-disaster travel data can help quantify the reliability of the simulation outcomes and, therefore, decrease the degree of uncertainty. The earthquake occurred on the 14th November 2016 NZDT, around 60km south-west of Kaikoura at a depth of 15km, resulting in widespread disruption and closure of sections of State Highway 1, which is a critical corridor in the South Island of New Zealand. The validation was undertaken against 7-day Average Daily Traffic (ADT) post-earthquake, returning an acceptable R squared value and line of best fit that met the validation criteria (NZTA, 2014).

2.4 Model Setup for Post-Disaster Scenario

The reported AF8 scenarios (included in the next section) are applied to the network using the link closure option in Aimsun. The assumption is that users have perfect knowledge of the event and disrupted roads in all of the selected scenarios for this study – this assumption is considered realistic given the coverage on traditional and social media following the earthquake. It also assumes that all trips included in the business-as-usual (BAU) model will be undertaken, except for trips with no accessibility – these are considered to be eliminated trips. Therefore, considering the classical four-step transportation modelling process (trip generation, trip distribution, modal split, and trip assignment) only the last step is assumed to be affected due to the blocked links. Users, therefore, are forced to change their routes where need, resulting in increased journey times.

Trips are assigned to the calibrated network applying mesoscopic dynamic assignment and a stochastic route choice C-Logit model. The corridor and district trip analyses are implemented using performance measures of the dynamic assignment, including mean travel time, total travel time, total travelled distance, and flow. The corridor analysis investigates how traffic counts vary on each corridor using accumulated volume for the whole analysis period (24 hours).

The trip analysis investigates the trip variation among traffic zones using different performance measures. Given that the traffic zones defined for this project are in unit areas, resulting in 541 traffic zones, it was therefore decided to group them into 23 districts, according to a StatsNZ (2018) dataset. The aggregated traffic data from all traffic zones in each district to other districts, including travel time and flow, are denoted as the district total travel time and district flow. The district travel cost (TC) is estimated by Equation 6 where D_i represents districts, ζ is a defined scenario (for instance one week or six months scenarios), and (0) represents BAU.

$$\mathrm{TC}^{D_i} = \frac{TC_{(\zeta)}^{D_i} - TC_{(0)}^{D_i}}{TC_{(0)}^{D_i}} \tag{4}$$

In addition to the travel cost variation, the other significant concern is the number of eliminated trips. When a link or a group of links on the network is blocked or disrupted, some traffic zones might be disconnected from other traffic zones, meaning that no trips will occur. In this case, the travel cost will be infinite and demand unsatisfied (Jenelius et al., 2006) or the eliminated trips will increase. Consequently, the number of eliminated trips is also estimated as part of the districts trip analysis.

3. Alpine Fault Earthquake (AF8) Scenario

New Zealand is an island nation with a land area of 268,107km^2 and a population of 4,509,700 (NZIP, 2015). Earthquakes, volcanoes, storms, and glaciers have shaped the landscape of New Zealand over millions of years (ODESC, 2007). It consists of two main islands; the South Island with a land area of 150,437km^2 and a population of 1,058,052, and the North Island with a land area of 113,729km^2 and a population of 3,294,543 (StatsNZ, 2018). The South Island is the larger island, dominated by the Southern Alps (ODESC, 2007), and contains seven regions and 23 districts. The transport network (road, rail, sea, and air) in New Zealand is well-developed and well-connected containing: 11,000km of state highways; 80,000km of local roads; seven international airports; 28 regional airports; 4,000km of rail track; and 14 exporting seaports (MOT, 2017). The road network, as the backbone of the transportation system, accounts for 84% of personal daily journeys and around 70% of freight tonne-kilometres (MOT, 2017). Although state highways cover just 12% of all roads in NZ, they carry around 50% of all flow (MOT, 2017).

Figure 3 shows the State Highways and districts in the South Island. State Highway 1 (SH1) connecting the north to the south of the Island, along the east coast, carries the majority of traffic on the network, as the main cities including Christchurch and Dunedin are located on this side of the Island. Corridors connecting Christchurch to Dunedin carry the highest traffic volume. Parallel to SH1, there is SH6 on the west coast starting from Marlborough (on the top of the Island) and ending in Invercargill (Southland District) where both SH1 and SH6 connect. Three corridors connect the east coast to the west coast, namely SH63, SH7 and SH73. In addition, SH6 connects the east and west, albeit at the very top of the island. In comparison to SH1, SH6 carries low traffic volumes on the west coast. The west coast is predominately a destination for tourists, with limited industries. The main ports and cities are all located on the east coast of the South Island, resulting in higher traffic volumes on this coast.

Figure 3: South Island State Highways and Districts

There are a number of active fault systems spread throughout the country. Robinson and Davies (2013) reported that only two earthquakes are attributed to the major fault systems in the South Island since European settlement, the 1848 Blenheim earthquake (Awatere fault) and the 1888 North Canterbury earthquake (Hope fault). In fact, most of the historical earthquakes in the South Island were attributed to minor faults, not major fault systems (Robinson and Davies, 2013). The Alpine fault is one of the major fault systems in New Zealand and extends all through the west coast. Given the high possibility of an Alpine fault rupture in the next 50 years and the consequential severe damage to lifelines, McCahon et al. (2006) stated that the effects of the AF8 earthquake will not be limited to only the West Coast and will, instead, influence the whole of the central South Island, including the main transportation corridors. Benn et al. (2002) reported that earthquakes (especially those associated with the Alpine Fault) have the potential to cause significant impact and damage to the West Coast Region.

The most recent study regarding the impact of AF8 on different infrastructure was developed by Davies (2019). He developed several scenarios in ten time-steps, namely one day, one week (7 days), one month (30 days), six months (183 days), one year (365 days), two years (730 days), three years (1095 days), four years (1461 days), five years (1826 days), and ten years (3652 days), for different infrastructure, including energy, telecommunication, water and wastewater, and transportation. Figure 4 shows the first five of the aforementioned scenarios for the road network. In the first scenario, one day after the earthquake, the condition of the network, the disrupted areas, and the severity of the damage are not as yet clear. In order to rectify that situation, investigations and reconnaissance are required by authorities to clarify the impact. One week after the earthquake, however, the NZ Transport Agency prioritise the opening of SH7, SH 65, and SH69 to lower Buller (Davies, 2019), although they will remain closed to all types of vehicles for at least one more month, at which time only emergency vehicles will be allowed to travel on a number of corridors (see Figure 4 (one month)). Given that access for emergency vehicles is not the main purpose of this study, one week/one month post-disaster are taken as a combined second scenario – this will simply be referred to as the one week scenario hereafter. It can be seen from Figure 4 (1 week) that SH65, SH69, SH7, and SH73 are closed. Except for a small part of SH6 connecting Greymouth to Hokitika, the rest of SH6 connecting SH65 on the North to Lake Hawea near Queenstown on the South will also be inaccessible. On the south-west part of the network, the whole of SH94 connecting Milford Sound to Te Anau will also be disrupted, resulting in a significant number of eliminated (unsatisfied) trips.

Six months after the earthquake, a number of corridors will be accessible for one to two days a week (see Figure 4 - 6 months), including SH65, SH7, SH69, and SH6 connecting Hokitika to Franz Josef. To run the network for this third scenario, it is assumed sections with one or two days accessibility in a week are open for the modelled day. Beyond six months after the earthquake, some parts of SH6, connecting Westport to Greymouth and connecting Franz Josef to Lake Hawea, and also SH73 will remain closed.

4. Corridor Analysis

Figure 5 shows the accumulated traffic count data on the road network at (a) BAU, (b) one day after, (c) one week after, (d) six months after, and (e) beyond six months after the AF8. Due to the Alpine fault earthquake, the two main highways connecting the east of the South Island to the west (SH7 and SH73) and most parts of SH6 will be completely blocked one day post-disaster causing three Districts (Buller, Westland, and Grey) on the west coast to be isolated (Figure 5(b)). Therefore, almost all local trips and inter-district trips from these three districts will be cancelled. One week post-disaster, some increase in trips will occur within and between the three aforementioned districts as roads are reopened to provide accessibility (Figure 5(c)). As a result, the traffic flow on SH1 between Marlborough and SH7, on the east coast of the South Island outside of the impacted areas, increases by 32% resulting in a 38% increase in total travel time. The section of SH6 connecting Nelson to Marlborough, will experience increased flow and total travel time of 25% and 32%, respectively (see Figure 5(b)).

Six months post-disaster, SH65 and SH7 return to full-functionality. As a result, compared to the one week scenario, fewer traffic zones will be blocked and more trips will be undertaken. The traffic flow on SH1 and SH6 connecting Nelson to Marlborough decreases by 22% and 19%, respectively, compared to the traffic flow one week post-disaster. However, SH65 and SH7 experience higher flows compared to BAU, 78% and 58%, respectively, due to the continued closure of SH73 and also SH6 between SH65 and SH69 (Figure 5(d)). While more corridors will be accessible beyond six months post-disaster, a number of corridors including SH7, SH69, and SH6 connecting Westport to SH69 experience increases in traffic flow of 63%, 36%, and 68% and increases in total travel time of 78%, 38%, and 68%, respectively, compared to BAU. However, the flow on SH65 decreases significantly due to the re-opening of SH6 between SH65 and SH69.

5. District Trip Analysis

The trip analysis of one day, one week, six months, and beyond six months after the earthquake indicates that around 12900, 7400, 2500, and 830 trips, 2.02%, 1.16%, 0.39%, and 0.13% of total trips, respectively, cannot occur due to accessibility issues, known as eliminated trips. Table 1 shows the number of eliminated trips for the four selected scenarios and for the three main impacted districts, namely Buller, Westland, and Grey. The results report that nearly 78% of the total eliminated trips one day post-disaster are generated from the aforementioned districts with 22%, 12%, and 44% of total eliminated trips, respectively. Comparing the number of eliminated trips one day post-disaster with the total BAU trips, it can be seen that 52%, 49%, and 45% of total trips from Buller, Westland, and Grey Districts, respectively, will not occur. As a result, the Buller District is the most impacted district with almost half of its trips cancelled (all inter-district trips and half of local trips) while the Grey District accounts for the highest number of eliminated trips, around 44% of total eliminated trips.

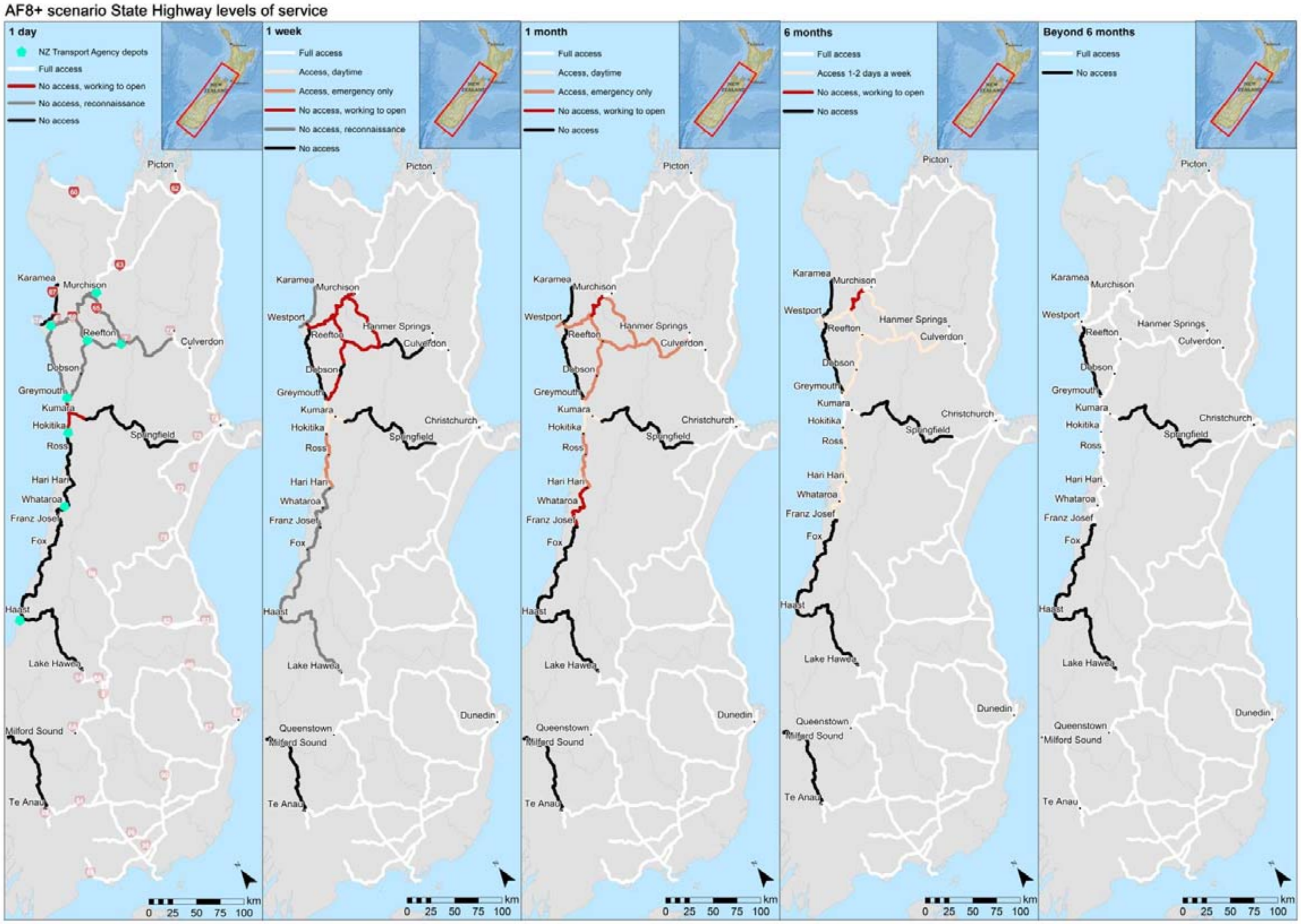

Figure 4: Expected Level of Services of the Road Network in Five Time Steps for AF8+ Scenarios *(Davies, 2019)*

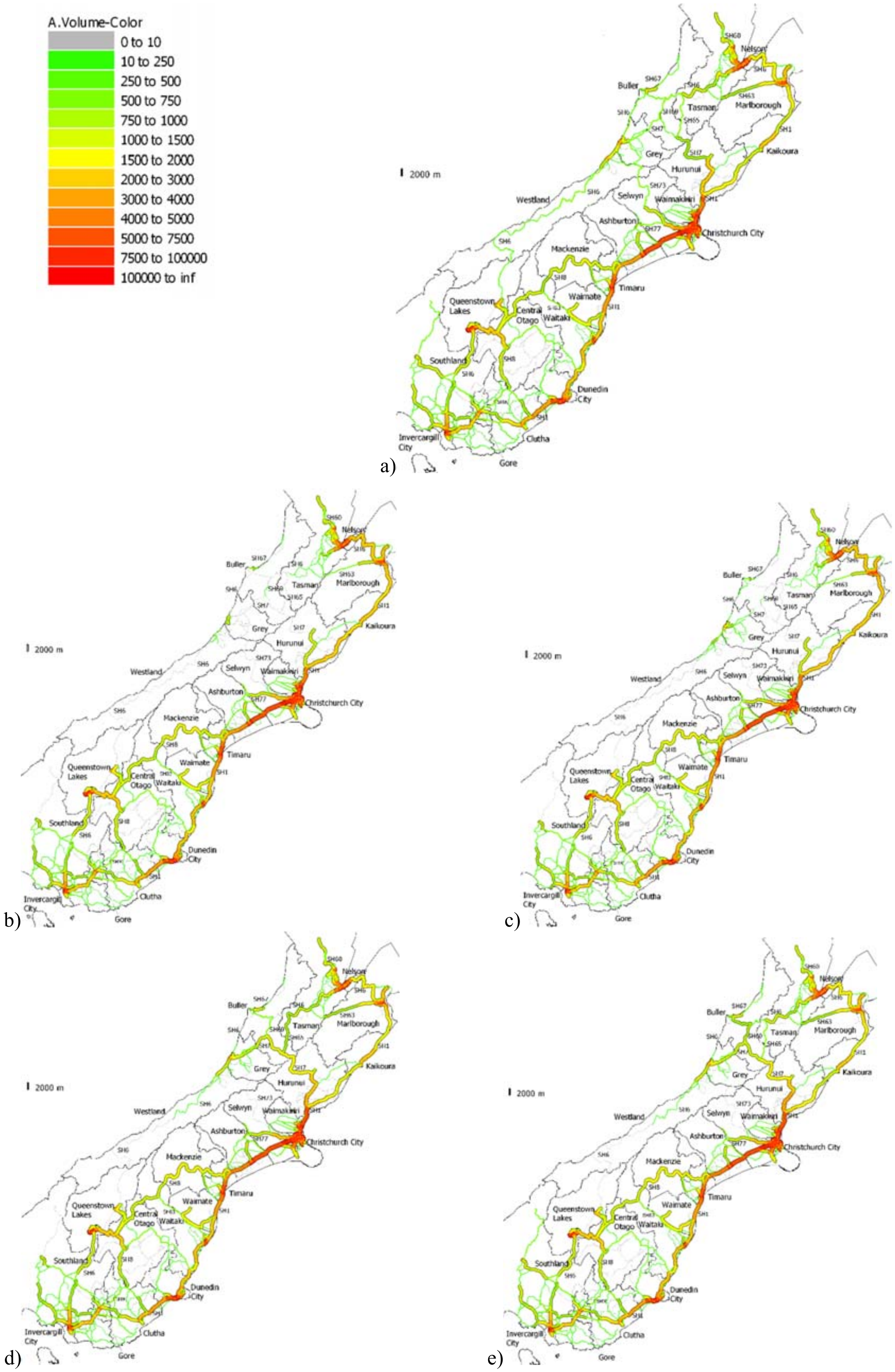

Figure 5: Daily Traffic Count Data (a) BAU, (b) One Day After, (c) One Week After, (d) Six Months After, and (e) Beyond Six Months After AF8

One week after the earthquake, a number of roads around Greymouth and SH6 connecting Greymouth to Hokitika will be reopened resulting in improved accessibility for local and inter-district trips. As a result, referring to Table 1 again, the number of eliminated trips from the Grey District decreased dramatically to 7% of BAU, although the situation in Buller is almost the same as one day post-disaster. More trips can also occur from Westland District, resulting in a reduction in eliminated trips from 49% to 28% of BAU. Given that six months post-disaster, a number of routes and corridors return to normal functionality, including SH7 and SH65, the number of eliminated trips from Buller, Westland, and Grey Districts will decrease to around 12%, 9% and 1% of BAU, respectively, as can be seen in Table 1. According to the last scenario, beyond six months post-disaster, the accessibility from Milford Sound on the south-east of the South Island will be re-established. While the number of eliminated trips in comparison to the total number of trips is insignificant, there are three traffic zones still isolated including Charleston unit area in the Grey District and Fox Glacier and Haast unit areas in the Westland District.

Variations in the selected traffic parameters for the three main impacted districts are also presented in Table 1, including total travel time and total travelled distance. Total travel time and total travelled distance decrease by more than 90% for the Buller district one day and one week post-disaster, given that almost 40% (around 1200 out of 2800 trips) of eliminated trips are inter-district trips, as seen in Table 2. After six months, only 12% of total trips from Buller district are blocked (Table 1) and the remaining trips to the other districts will take place, although with increased travel cost (travel time) for some users compared to BAU. Table 2 indicates travel time to Marlborough, Nelson, Queenstown, Tasman, Grey, and Central Otago increases by around 20-30%, compared to BAU. Finally, referring to Table 1 again, beyond six months post-disaster, 4% of trips from Buller district are eliminated which equates to a 6% reduction in total travel time compared to BAU. Referring to Table 2, travellers to Queenstown and Grey districts experience a 33% and 46% increase in travel time, respectively. However, due to the reopening of SH6 between SH65 and SH69, travel time to Marlborough, Tasman, and Nelson decrease significantly.

Table 1: Overall Traffic Parameters Variation from the Three Most Impacted Districts

Traffic Parameters	Scenarios	Total Network	Buller	Westland	Grey
Daily Number of Trips	**BAU**	637,620	5,469	3,223	12,689
Daily Trips Variation	**Day1**	-2.02%	-52%	-49%	-45%
	Week 1	-1.16%	-51%	-28%	-7%
	Month 6	-0.39%	-12%	-9%	-1%
	Month6+	-0.13%	-4%	-7%	-1%
Total Travel Time (min)	**BAU**	15,738,549	296,036	223,271	299,429
Total Travel Time Variation	**Day1**	-8.39%	-93%	-91%	-83%
	Week 1	-7.74%	-93%	-80%	-58%
	Month 6	-1.21%	-28%	-10%	5%
	Month6+	0.04%	-6%	-5%	7%
Total Travelled Distance (km)	**BAU**	19,160,071	399,724	291,902	381,201
Total Travelled Distance Variation	**Day1**	-9.40%	-93%	-91%	-86%
	Week 1	-8.68%	-92%	-80%	-59%
	Month 6	-2.22%	-28%	-10%	5%
	Month6+	0.02%	-7%	-5%	8%

Referring to Table 1, the Westland district, where around half of users will be blocked in one day post-disaster, will have a reduction of 91% in total travel time due to the significant destruction of the road network on SH6, the main corridor in the district. One week after the earthquake, 28% of trips will still be cancelled which equates to an 80% reduction in total travel time compared to BAU. It can be seen from Table 3 that, except for the majority of local trips and limited trips to Grey and Buller (after one week), the rest of the inter-district trips will be cancelled for around six months post-disaster. After six months and beyond six months, 9% and 7% of users are still blocked, with users taking longer distance routes resulting in increased travel time for those trips that can occur, as can be seen in Table 3. Travel time to Queenstown from Westland increased by around 170%, for instance, due to the increase in travelled distance. Travellers to Ashburton, Southland, Selwyn, Waitaki, Mackenzie, Dunedin, and Christchurch will experience around 40-80% increase in travel time from Westland. The fact is that most parts of SH6 connecting Franz Josef to Queenstown are still closed six months after the earthquake, resulting in long alternative trips for users.

Table 2: Flow and Travel Time Variation from Buller District Comparing Four Scenarios

Districts/ Scenarios	**BAU TT (min)**	**Average Travel Time (TT) Variation (min)**				**BAU Trips (#)**	**Eliminated Trips (#)**			
		Day1	**Week1**	**Month6**	**Month6+**		**Day1**	**Week 1**	**Month 6**	**Month 6+**
Buller	12	-6(-49%)	-5(-45%)	-2(-17%)	-1(-5%)	4,267	-1622	-1622	-231	-64
Westland	149	Blocked	-53(-36%)	4(3%)	19(13%)	319	-319	-302	-119	-61
Christchurch	253	Blocked	Blocked	-6(-2%)	8(3%)	308	-308	-308	-72	-15
Grey	81	Blocked	-19(-24%)	14(17%)	38(46%)	216	-216	-210	-90	-44
Marlborough	238	Blocked	Blocked	64(27%)	(0%)	145	-145	-145	-35	-4
Queenstown	433	Blocked	Blocked	122(28%)	142(33%)	70	-70	-70	-39	-26
Nelson	208	Blocked	Blocked	53(26%)	-1(0%)	46	-46	-46	-22	-8
Tasman	206	Blocked	Blocked	48(23%)	1(0%)	24	-24	-24	-9	-2
Selwyn	256	Blocked	Blocked	9(3%)	37(14%)	23	-23	-23	-9	-3
Waimakariri	211	Blocked	Blocked	-23(-11%)	6(3%)	15	-15	-15	-5	0
Ashburton	286	Blocked	Blocked	23(8%)	54(19%)	12	-12	-12	-10	-5
Hurunui	150	Blocked	Blocked	2(2%)	2(2%)	5	-5	-5	0	0
Timaru	312	Blocked	Blocked	24(8%)	28(9%)	4	-4	-4	-2	-2
Dunedin	502	Blocked	Blocked	Blocked	79(16%)	4	-4	-4	-4	-2
Otago	452	Blocked	Blocked	80(18%)	80(18%)	7	-7	-7	-5	-5
Invercargill	595	Blocked	Blocked	13(2%)	26(4%)	2	-2	-2	-1	-1
Mackenzie	359	Blocked	Blocked	38(11%)	43(12%)	2	-2	-2	0	0
Total	-	-	-	-	-	5,469	-2824	-2801	-653	-242

Table 3: Flow and Travel Time Variation from Westland District Comparing Four Scenarios

Districts/ Scenarios	**BAU TT (min)**	**Average Travel Time (TT) Variation (min)**				**BAU Trips (#)**	**Eliminated Trips (#)**			
		Day1	**Week1**	**Month6**	**Month6+**		**Day1**	**Week 1**	**Month6**	**Month 6+**
Westland	16	-4(-26%)	-4(-24%)	-3(-16%)	-3(-16%)	1,785	-159	-74	-33	-33
Grey	57	-11(-19%)	-20(-35%)	-10(-18%)	-10(-18%)	692	-686	-93	-34	-34
Buller	144	Blocked	-54(-38%)	6(4%)	25(17%)	294	-294	-287	-124	-65
Christchurch	217	Blocked	Blocked	89(41%)	89(41%)	201	-201	-201	-27	-27
Marlborough	306	Blocked	Blocked	28(9%)	-1(0%)	72	-72	-72	-3	-1
Queenstown	244	Blocked	Blocked	415(170%)	420(172%)	44	-44	-44	-32	-31
Nelson	304	Blocked	Blocked	18(6%)	-12(-4%)	32	-32	-32	-3	-3
Selwyn	199	Blocked	Blocked	125(63%)	124(62%)	21	-21	-21	-5	-5
Tasman	236	Blocked	Blocked	9(4%)	-4(-2%)	19	-19	-19	-1	0
Hurunui	293	Blocked	Blocked	5(3%)	6(3%)	16	-16	-16	0	0
Waimakariri	218	Blocked	Blocked	76(35%)	77(36%)	15	-15	-15	0	0
Southland	435	Blocked	Blocked	338(78%)	343(79%)	10	-10	-10	-7	-7
Mackenzie	329	Blocked	Blocked	184(56%)	187(57%)	8	-8	-8	-1	-1
Waitaki	380	Blocked	Blocked	207(54%)	199(52%)	5	-5	-5	-2	-2
Otago	237	Blocked	Blocked	Blocked	Blocked	3	-3	-3	-3	-3
Kaikoura	270	Blocked	Blocked	11(4%)	19(7%)	2	-2	-2	0	0
Ashburton	235	Blocked	Blocked	194(83%)	201(85%)	2	-2	-2	-1	-1
Dunedin	431	Blocked	Blocked	212(49%)	217(50%)	1	-1	-1	0	0
Total	-	-	-	-	-	3,223	-1,591	-906	-277	-214

Referring to Table 1, one day after the earthquake regional access roads to Greymouth will be disrupted causing elimination of nearly half of trips and a reduction of 83% of total travel time. By providing more accessibility to other traffic zones in the Grey, Westland, and Buller districts one week post-disaster, the majority of local trips and inter-district trips will occur, and only around 7% of BAU trips will be eliminated. However, it can be seen that the overall total travel time and total travelled distance decreased by just under 60% compared to BAU, indicating that almost all of the eliminated trips from the Grey district are inter-district trips. After six months, the accessibility of the Grey district to other districts, except some traffic zones in the Westland district (over 1% of total trips), are possible, although with increased travel time. Referring to Table 4, the increase in travel time from the Grey district, six months after the earthquake, generally relates to the rise of inter-district travel time. For instance, travel time to Selwyn will be almost doubled up to six months after the earthquake due to the continued disruption on SH73. Similarly, travellers to other districts, including Queenstown, Mackenzie, Christchurch, Buller, and Timaru will experience increased travel time, as they have to take a longer alternative route using SH7 instead of SH73. However, for travellers to Marlborough, Tasman, and Nelson the situation improves by around 30 minutes, as the section of SH6 connecting these districts to the West Coast Region will be reopened.

Table 4: Flow and Travel Time Variation from Grey District Comparing Four Scenarios

Districts/ Scenarios	BAU TT (min)	Average Travel Time (TT) Variation (min)				BAU Trips (#)	Eliminated Trips (#)			
		Day1	Week1	Month6	Month6+		Day1	Week1	Month6	Month6+
Grey	9	-2(-21%)	0(1%)	0(2%)	0(0%)	11211	-4221	-2	0	-1
Westland	57	-24(-42%)	-18(-32%)	-8(-15%)	-8(-14%)	668	-659	-92	-27	-27
Christchurch	198	Blocked	Blocked	68(35%)	68(34%)	296	-296	-296	-12	-12
Buller	80	Blocked	-23(-29%)	21(26%)	42(52%)	213	-213	-210	-96	-51
Queenstown	378	Blocked	Blocked	204(54%)	204(54%)	103	-103	-103	-33	-29
Marlborough	267	Blocked	Blocked	31(12%)	2(1%)	77	-77	-77	-1	0
Hurunui	161	Blocked	Blocked	6(4%)	5(3%)	35	-35	-35	0	0
Nelson	217	Blocked	Blocked	33(15%)	1(1%)	29	-29	-29	0	0
Selwyn	153	Blocked	Blocked	145(94%)	145(94%)	22	-22	-22	-2	-2
Tasman	182	Blocked	Blocked	30(16%)	3(1%)	12	-12	-12	0	0
Timaru	265	Blocked	Blocked	91(34%)	91(35%)	7	-7	-7	0	0
Waimakariri	185	Blocked	Blocked	55(30%)	55(30%)	7	-7	-7	0	0
Kaikoura	235	Blocked	Blocked	12(5%)	12(5%)	5	-5	-5	0	0
Southland	638	Blocked	Blocked	Blocked	166(26%)	2	-2	-2	-2	0
Mackenzie	348	Blocked	Blocked	106(30%)	119(34%)	2	-2	-2	0	0
Total	-	-	-	-	-	12689	-5690	-901	-173	-122

6. Heavy Vehicle Movements Analysis

Heavy vehicle travel demand is divided into two parts in this study: freight demand and tourism demand. The road network carries the majority of freight movements in New Zealand, accounting for 91% of tonnes and 70% of tonne-km (NFDS, 2014). Domestic, export and import freight movements account for 66%, 28% and 6%, respectively, of total freight movements in New Zealand (NFDS, 2014). In case of a disaster and disruption on the network, the freight movements, similar to other trip purposes, will be cancelled, postponed, shifted to other modes, or experience increased travel cost.

Following the AF8 earthquake, the HV inter-district movements from the three most impacted districts will be disrupted experiencing cancellation or increased travel time. Table 5 shows the eliminated trips (number of trips and percentage) from Buller, Grey and Westland Districts. One day post-disaster, 70%, 86%, and 81% of heavy vehicle trips from Buller, Grey, and Westland, respectively, are eliminated. The HV movements from Grey and Westland will improve moderately one week after the earthquake, while from Buller the number of cancelled trips decrease slightly. Given the situation on the network six months post-disaster, only 17%, 5%, and 11% of HV trips from Buller, Grey, and Westland, respectively, cannot occur. The number of eliminated trips from Buller decrease beyond six months post-disaster, while from Grey and Westland only slight change can be seen.

Table 5: Eliminated Heavy Vehicle Trips from Three Most Impacted Districts Comparing Four Scenarios

Districts	BAU Trips (#)	Eliminated Trips (#)			
		Day1	Week1	Month6	Month6+
Buller	287	-202 (-70%)	-184 (-64%)	-48 (-17%)	-13 (-5%)
Grey	384	-330 (-86%)	-157 (-41%)	-21 (-5%)	-17 (-4%)
Westland	238	-192 (-81%)	-113 (-47%)	-25 (-11%)	-24 (-10%)

7. Conclusion

New Zealand is a country with a number of active fault systems spread throughout the country. Since 2010, three major earthquakes have occurred in NZ, all in the South Island, causing 184 deaths and an estimated US$28.450 billion in damage. The Alpine fault, one of the major fault systems in New Zealand, extends all through west coast with a high possibility of a rupture in the next 50 years, meaning that the next large earthquake on the Alpine Fault is likely to occur within our, or our children's, lifetime. Consequential severe damage to lifelines, including the main transportation corridors, is also predicted. Although the physical impact of the AF8 has been studied in detail, there is a paucity of research in the literature assessing the operational performance of the road network following such an event.

Consequently, this research developed a methodology to simulate post-disaster transportation impacts on a large regional road network. This included the base model development, model calibration and validation in a post-disaster situation. The methodology was demonstrated using the road network for the South Island of New Zealand, however, it is equally applicable elsewhere using equivalent data from other countries or regions. The model was then applied to evaluate the operational performance of the South Island road network following a potential Alpine Fault Magnitude 8 earthquake. The model uses a combination of simulation software, developed in Aimsun Next 8.3.0, and analytical methods to assess the operational performance. The South Island was divided into 541 traffic zones representing New Zealand (NZ) geographic unit areas based on census data. In addition, 622 detectors were located at 311 locations on the state highways. The corridor and district trip analysis were implemented using the outputs of the dynamic assignment, including mean travel time, total travel time, total travelled distance, and flow.

Four scenarios developed by Davies (2019) were selected as the main source of disruption on the network, namely one day, one week, six months, and beyond six months after the earthquake. Almost all inter-district trips, and some local trips, from the three main impacted districts, namely Buller, Grey and Westland, one day and one week post-disaster will be eliminated, around 12900 (2.02%) and 7400 (1.16%) trips, respectively. Typically, trips that can occur will take alternative routes, causing a 32% increase in flow on SH1 between Marlborough and SH7, and a 25% increase in flow on SH6 connecting Nelson to Marlborough.

Six months post-disaster, SH65 and SH7 return to full-functionality, providing a connection between the east and west coast. This results in a reduction of around 12%, 9% and 1% of BAU trips from Buller, Westland, and Grey, respectively. The traffic flow on SH1 and SH6 connecting Nelson to Marlborough decreases by 22% and 19%, respectively, compared to the flow one week post-disaster. However, SH65 and SH7 experience higher flow compared to BAU, 78% and 58%, respectively. Travel time to Queenstown, for instance, increased by around 170%, 28%, and 54% from Westland, Buller, and Grey, respectively.

While more corridors will be accessible beyond six months post-disaster, a number of corridors including SH7, SH69, and SH6 connecting Westport to SH69 experience increases in traffic flow of 63%, 36%, and 68% and increases in total travel time of 78%, 38%, and 68%, respectively, compared to BAU. However, the flow on SH65 decreases significantly due to the reopening of SH6 between SH65 and SH69.

Following the AF8 earthquake, the HV inter-district movements from the three most impacted districts will be disrupted experiencing cancellation or increased travel time. One day post-disaster, for instance, 70%, 86%, and 81% of heavy vehicle trips from Buller, Grey, and Westland, respectively, are eliminated.

The outputs from this model will provide emergency response and transportation organisations with critical information regarding the performance of the network following an Alpine Fault Magnitude 8 earthquake. Such information will help them plan for, and respond to, such an event.

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