Assessing Operational Performance of New Zealand's South Island Road Network after the 2016 Kaikoura Earthquake

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Abstract

The Kaikoura earthquake, a 7.8 (Mw) magnitude event, occurred two minutes after midnight on 14th November 2016 NZDT, around 60km south-west of Kaikoura at a depth of 15km. The earthquake caused numerous landslides, many of them significant, resulting in widespread disruption and closure of sections of State Highway 1 (SH1), which is a critical corridor in the South Island of New Zealand. Post-disaster operational performance of the road network, in terms of average travel time, density, and count data, has not been assessed to date. A mesoscopic traffic simulation model of the South Island’s road network was, therefore, validated against 7-day Average Daily Traffic (ADT) data starting from Day 8 after the Kaikoura earthquake. Corridor analysis and trip analysis were conducted to assess post-disaster operational performance of the road network. Corridor analysis results indicate a significant increase in traffic count and density, and a minor decrease in average travel speeds on four main corridors namely: SH65, SH63, SH6 (between SH63 and SH65), and SH7 (between SH65 and SH1), serving as the main alternative routes after the earthquake. Trip analysis results show a significant increase in the average travel time from Marlborough to other affected traffic zones (typically 20-50% and as much as 90% in the worst case) due to the increased travel distances on the alternate routes. Such information can now be used to calculate the economic impact of the Kaikoura earthquake, in terms of increased vehicle operating costs and travel time costs, by comparing the pre- and post-disaster scenarios.

Key Words: Operational Performance, Corridor Analysis, Trip Analysis, Kaikoura Earthquake, Traffic Simulation, Road Network, Validation.

1. INTRODUCTION

Disaster trends indicate that communities are increasingly becoming more vulnerable to disasters, and that risks are rising globally (Mayunga, 2007, Ainuddin and Routray, 2012). However, risk reduction measures are often ignored until the occurrence of disasters (Cutter et al., 2008). Natural hazards can affect communities structurally, environmentally, socially, and economically. Disturbance or destruction of infrastructure can destabilize society, and can impact the economy, health and safety of the community as the functioning of communities is closely related to infrastructure functionality, especially in response to disasters and during an evacuation (Normandin et al., 2011). The transportation system, a critical infrastructure lifeline, is a multi-modal, multi-faceted, and multi-parametric system distinguished by a variety of complex and non-linear interrelationships and interdependencies between the physical system, information system, system users, and external components at the micro and macro level (Tamvakis and Xenidis, 2012). Although transportation systems are mainly designed for daily commuting and freight services’ on a day-to-day basis, the transportation system can also assist in the rescue operation and recovery of other lifelines following a disaster (Mattsson and Jenelius, 2015). The impact of a transportation system failure in an urban, compared to a rural area, can be quite different, depending on the extent of road network damage. Generally, several alternative routes are available in cities, which is seldom the case in rural areas. Transportation network failure influences the connectivity and overall system performance (Taylor et al., 2006).

The functionality of a road network following a disaster can be assessed based on asset performance and operational performance. Disasters cause damage to transportation assets such as bridges, tunnels, and roads, which in turn can influence the operational performance of the network, as measured by different traffic parameters including variation in capacity, average travel time, delay time, and density. Understanding operational performance of the transportation network following a disaster is crucial for post-disaster operations and business continuity.

The approaches used in the literature to assess the performance of transportation networks following a natural disaster, can be broadly classified into three categories, namely: conceptual, analytical and a combination of analytical and simulation. The conceptual approach considers qualitative methods to estimate the performance of the network employing questionnaires and statistical methods to examine the resilience of the network, mostly structurally and organizationally (Mason and Brabhaharan, 2016, Wang, 2015, Hughes and Healy, 2014, Tamvakis and Xenidis, 2012, Brabhaharan et al., 2006). Since they do not analyse the post-disaster operational performance of the network, they are typically only used for organizational emergency and strategic plans. For instance, Hughes and Healy (2014) developed one such conceptual framework to estimate the resilience of the New Zealand (NZ) transportation network.

The analytical approach employs various mathematical models and indices to assess the operational performance of the network (Ilbeigi, 2019, Zhang and Wang, 2016, Soltani-Sobh et al., 2016, Pokharel and Ieda, 2016, Zhang et al., 2015, Miller-Hooks et al., 2012, Taylor et al., 2006, Jenelius et al., 2006), depending on data availability, the aim of the study, the specify case study under consideration, computational capability, and the type of hazard. One of the main drawbacks of the analytical approach is the fact that it is complex and computationally intensive, especially for large-scale networks (Luathep et al., 2011).

The third approach, implemented in this study, is a combination of analytical and simulation methods. This approach utilizes transportation simulation software to model the network in order to estimate the required traffic flow parameters and, then, employs analytical methods to evaluate the network performance. While one of the most common uses of transportation simulations in disasters is in the calculation of clearance time in the event of an evacuation (Chen et al., 2006, Balakrishna et al., 2008, Naghawi and Wolshon, 2010, Zhang et al., 2013), it has also been applied to estimate the shortest distance or shortest travel time in a disrupted road network (Scott et al., 2006, Erath et al., 2009, Taylor et al., 2006). Using simulation software together with analytical methods improves computational efficiency and running time, especially for large-scale networks and can also facilitate the process of entering the input data and interpreting the results (TRB, 2010).

NZ has experienced several natural disasters in recent decades. Among those, earthquakes have caused the highest number of causalities (184 deaths) and economic loss (US$28.5 billion) (EM-DAT, 2017). Three major earthquakes have hit NZ in recent years, all located in the South Island which lies on a zone of continental convergence of the Pacific tectonic plate and Australian plate (Potter et al., 2015), including the Canterbury Earthquakes in 2010 and 2011, and the Kaikoura Earthquake in 2016. Potter et al. (2015) reports the impacts of the 2010 and 2011 Canterbury earthquakes on the natural, built and social environment, as well as the economy. The 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 related to transportation infrastructure (road and rail).

This paper is part of a wider research programme tasked with developing a network model capable of simulating the post-disaster operational performance of the South Island road network in NZ. The programme is primarily focussed on a potential future Alpine Fault earthquake due to the likelihood that the next large earthquake on the Alpine Fault will occur within our, or our children's, lifetime (Berryman et al., 2014, Benn et al., 2002). The Alpine Fault runs for over 600km up the spine of the South Island and is part of the active boundary between the Pacific and Australian tectonic plates and has an unusually regular history of producing large earthquakes.

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 in a post-disaster environment can help quantify the reliability of the simulation outcomes and, therefore, decrease the degree of uncertainty. The Kaikoura Earthquake provided a unique opportunity to validate the South Island road network model in a post-disaster situation, something that has not been attempted to date. Indeed, a review of the relevant literature would also suggest that a post-earthquake validation of a transportation model has not been undertaken elsewhere.

Furthermore, although the impact of the Kaikoura earthquake on the road assets and business operability, especially bridges and roads, has been investigated by Dizhur et al. (2019), Herbert et al. (2018), Davies et al. (2017), Brabhaharan et al. (2017), Mason et al. (2017), ME (2017) and Palermo et al. (2017), the impact of the earthquake on the operational performance of the network in terms of count data, travel time, and density, has not been examined to date. Consequently, having validated the network model, the opportunity to examine the post-disaster operational performance of the network was taken.

This research, therefore, has two main objectives. Firstly, the validation of a previously developed South Island road network model (Aghababaei et al., 2019) in a post-disaster scenario and, secondly, the assessment of the operational performance of the road network in a post-disaster environment. A mesoscopic traffic simulation model of the South Island's road network, developed in Aimsun (Advanced Interactive Microscopic Simulator for Urban and Non-urban Networks), was validated, first, against business-as-usual (BAU) Annual Average Daily Traffic (AADT) data, and then against 7-day Average Daily Traffic (ADT) data starting from Day 8 after the Kaikoura earthquake. Corridor analysis and trip analysis are conducted to assess post-disaster operational performance of the road network. Finally, the main findings of this research are summarized in the conclusion, along with opportunities for further research.

2. METHODOLOGY

A traffic simulation model of NZ's South Island regional road network was developed in Aimsun to assess the operational performance of the road network after the 2016 Kaikoura earthquake. The road network was initially created using Open Street Map (OSM) as the base road network, and then modified as required. The base model contains 541 traffic zones (TZs) based on NZ geographic unit areas of census data, and 622 detectors located at 311 locations providing excellent coverage of the main highways and corridors. The supply and demand data for the whole South Island were created based on three main travel purposes, namely commuting, tourism, and freight. The required data were obtained from 2013 census data, land use GIS shapefiles, the Regional Tourism Organisation (RTO) website, and Ministry of Transport (MOT) data. The combination of matrix estimation parameters, route choice parameters, link parameters, and driver behaviour parameters were applied at the macro level of simulation, and then mesoscopic, to calibrate against 2013 AADT data. Readers are referred to Aghababaei et al. (2019) for further detail. Figure 1 shows the location of districts in the South Island, as well as the state highways.

The overall methodology for validation of the regional road network and the assessment of the operational performance following the Kaikoura earthquake is presented in Figure 2. Travel behaviour, land use, trip purposes, number of trips, and demographics of an area change over time causing trip pattern changes among traffic zones. Given that the travel demand was created based on a 2013 dataset, to estimate trip changes three years later, matrix estimation methods were utilised. Three frequently used methods to estimate the demand matrix for the network include direct sample estimation, model estimation, and estimation from count data (Cascetta, 1984). The last one, used in this study, aims to adjust the matrix based on the observed traffic count data on the network. 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 method proposed by TSS (2017) is based on a "bi-level model solved heuristically by gradient algorithm and includes an assignment at each iteration". The outputs of the matrix estimation process, adjusted OD matrices and static path assignments, were applied to the network dynamically. An Intel® Xeon® Gold 6134 CPU @ 3.20GHz 3.19GHz (2processors) with 128GB memory was used to run static and dynamic assignments in Aimsun Next 8.3.0. Given that the road network has already been calibrated dynamically at the mesoscopic level for 2013 data by Aghababaei et al. (2019), the new OD matrices were assigned to the network using the same parameters for Stochastic Route Choice (SRC) C-Logit model (refer to Scenario1, Figure 2).

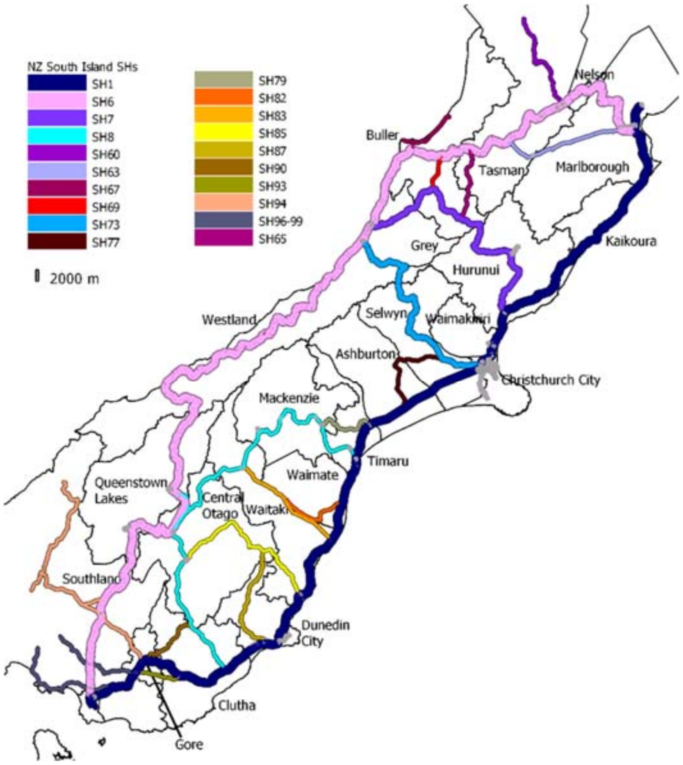


Figure 1: South Island State Highways and Districts

While the model was calibrated dynamically based on AADT data (Aghababaei et al., 2019), it is recommended to validate the model applying a different set of data, such as travel time or traffic count data of a specific date, instead of using AADT. It is widely recognised that the validation data set should differ from the calibration data set. NZTA (2014) recommends two sets of data, demand data which relates to the movement of vehicles, and performance data which relates to the performance of the network. This network will be validated using 7-day ADT traffic count data on several selected corridors from Day 8 after the Kaikoura earthquake, Scenario 2 in Figure 2. The level of service of the road network for Day 8 after the earthquake was extracted from Davies et al. (2017). Given that there is no available data regarding the number of cancelled or postponed commuting, tourism, and freight trips after the earthquake, it assumes that the traffic demand is inelastic and all trips included in the BAU model will be undertaken, but with no trips to/from the two traffic zones in the impacted area. Therefore, the same OD matrix as BAU was applied to the Day 8 scenario and users were forced to change their routes where needed, resulting in increased journey times.

The recorded 7-day ADT traffic count data from detectors above Ashburton District (refer to Figure 7), the most impacted area by the earthquake, were extracted and utilised to validate the model. It was assumed that users have knowledge of the event and disrupted roads eight days after the event – this assumption is considered realistic given the coverage on traditional and social media following the earthquake. Finally, as per the methodology outlined in Figure 2, the operational performance of the road network was evaluated using corridor and trip analysis of the impacted area.

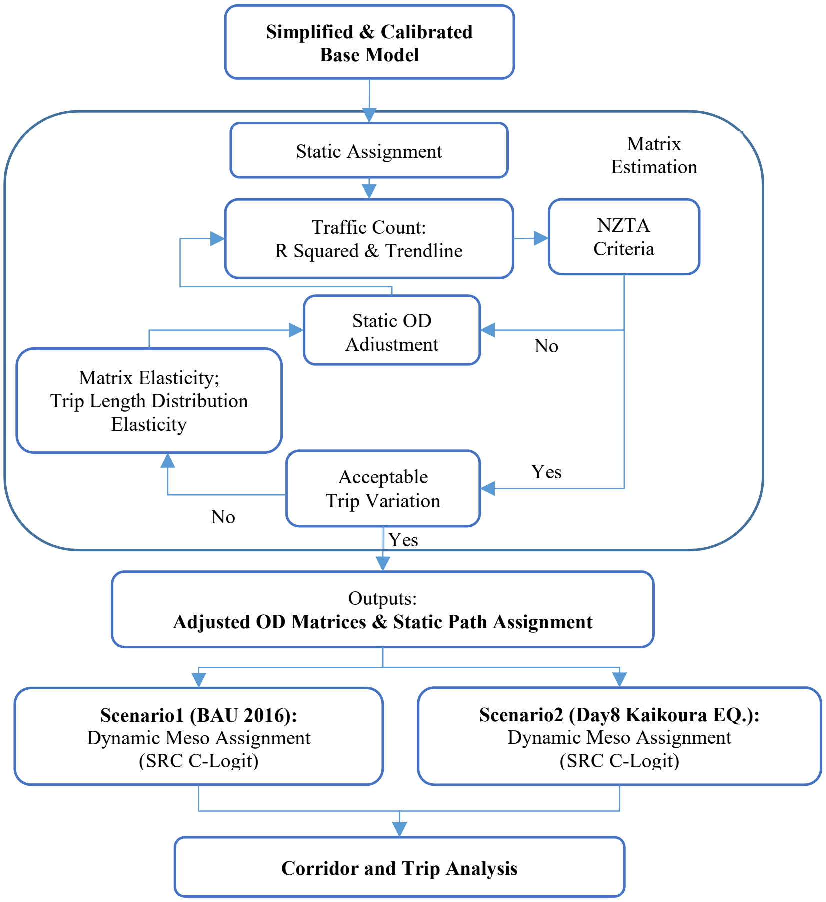


Figure 2: Methodology to Assess the Operational Performance of the Road Network to Natural Disasters

3. MATRIX ESTIMATION AND BAU VALIDATION PROCESS

A summary of the static OD adjustment process is presented in Table 1. The total number of trips increased by 5.55% with the highest increase in commuting trips, at 3.83% of total trips. Given that commuting trips typically represent relatively short trips between adjacent traffic zones, the commuting trips variation indicates a rise in local and intra-city trips. Tourism trips increased by 11.38% representing 1.22% of total trips. Freight movements increased by 11.8% compared to 2013 trips, accounting for an increase of just 0.50% of total trips.

Table 1: Summary of Static OD Adjustment Process

Trip types	Number of trips in 2013	Number of trips in 2016	Variations	Weighted Variation
Commuting	516,217	539,469	4.50%	3.83%
Tourism	65,082	72,488	11.38%	1.22%
Heavy Vehicles (Freight)	25,790	28,834	11.80%	0.50%
Total	607,089	640,791	-	5.55%

The new hourly traffic demand was created using the above mentioned three sets of adjusted OD matrices and hourly traffic profiles were calculated based on available Average Weekday Hourly Traffic (AWHT) for 42 sites on the whole network. These were assigned to the model statically and validated against 2016 AADT, resulting in an acceptable line of best fit with an R squared value of 99.5% (Figure 3(a)).

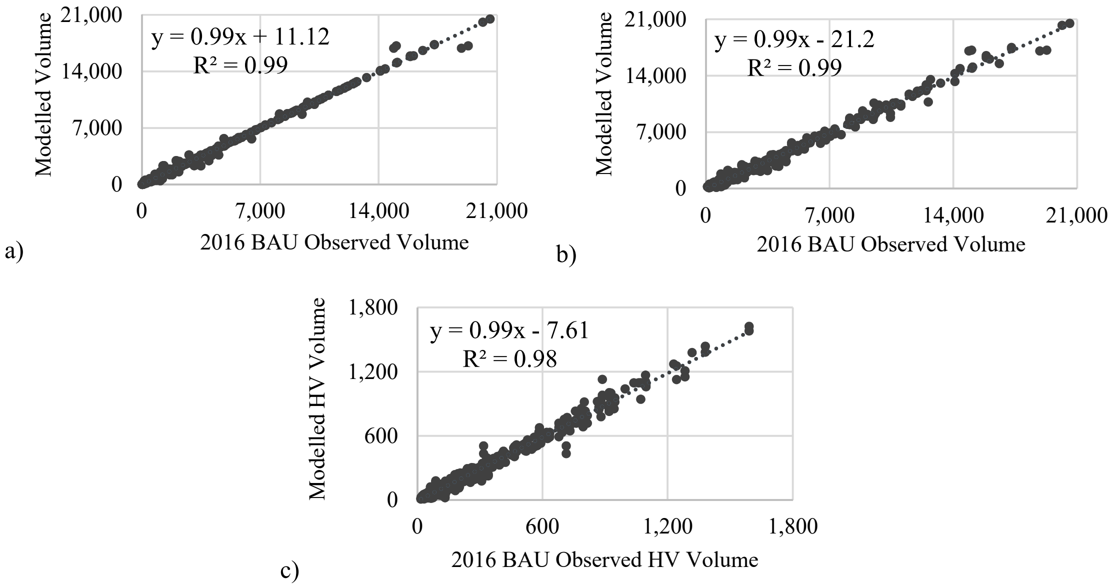
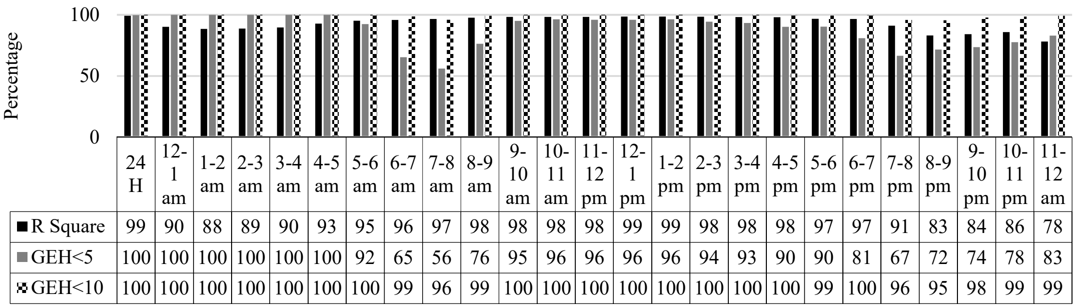


Figure 3: Scatter Plots for (a) Static Assignment Using 2016 Adjusted Demand (b) Dynamic Assignment Using 2016 BAU Demand (c) Dynamic Assignment Using 2016 BAU Demand for HV only

To validate the model dynamically, the three adjusted OD matrices and static path assignment, extracted from the static OD adjustment process, were applied as an input for the dynamic assignment scenario. The Stochastic Route Choice C-Logit method, and the same calibration parameters, including scale (a C-Logit parameter), number of shortest paths, attraction weight, centroid connections, and Beta (a C-Logit parameter) (Aghababaei et al., 2019) were utilised for this model. Since this project is modelling a large regional road network, "type A: Regional Transport Model" was selected with an acceptable R squared value defined as greater than 85% and a line of best-fit between y = 0.9x and y = 1.1x (NZTA, 2014). The result illustrates an acceptable line of best fit with an R squared value of 98.96%, as shown in Figure 3(b). Comparing the heavy vehicle simulated volume with observed volume indicates an acceptable line of best fit with an R squared value of 97.96% (Figure 3(c)).

The outputs from the mesoscopic loading under BAU indicates a total input count of 639,607 vehicles and flow of 26,565 veh/hr with no vehicles waiting to enter the network. Total travel time for all modes is 263,727 hours with 18,351,643 km total travelled distance.

According to NZTA (2014) modelling guidelines, in addition to having an acceptable R squared value, the hourly GEH<5 and GEH<10 should be greater than 60% and 90%, respectively, for "type A: Regional Transport Model". Referring to Figure 4, while the GEH<10 are all within the acceptable range, the GEH<5 is just below the threshold for the 7-8am interval (56%). This is better explained by the fact that the travel directionality has been assumed as 50:50, whereas during peak hours this is different with a higher demand in one direction.



	24 H	12-1 am	1-2 am	2-3 am	3-4 am	4-5 am	5-6 am	6-7 am	7-8 am	8-9 am	9-10 am	10-11 am	11-12 pm	12-1 pm	1-2 pm	2-3 pm	3-4 pm	4-5 pm	5-6 pm	6-7 pm	7-8 pm	8-9 pm	9-10 pm	10-11 pm	11-12 am
■ R Square	99	90	88	89	90	93	95	96	97	98	98	98	98	99	99	98	98	98	97	97	91	83	84	86	78
▨ GEH<5	100	100	100	100	100	100	92	65	56	76	95	96	96	96	96	94	93	90	90	81	67	72	74	78	83
⁙ GEH<10	100	100	100	100	100	100	100	99	96	99	100	100	100	100	100	100	100	100	99	100	96	95	98	99	99

Figure 4: GEH Results for Mesoscopic Assignment Using 2016 BAU AADT Data

As previously mentioned, NZTA (2014) suggest using one of the performance parameters, such as travel time, to validate the network. Therefore, the general performance of the network in BAU was validated by comparing the average travel time along 36 selected corridors, extracted from Google Maps, against simulated travel times in the model. The scatter plot, presented as Figure 5, indicates an excellent line of best fit, returning an R squared value of 99%. This indicates that the network is not only performing well based on demand data, but that it also performs well based on travel time on different corridors. Given that the model now has been validated against 2016 BAU AADT data and BAU travel time data, the next two sections will examine the validation of the model for a post-disaster scenario.

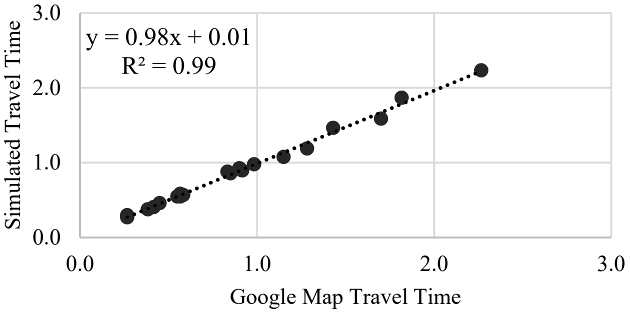


Figure 5: Travel Time Validation for 2016 BAU

4. KAIKOURA EARTHQUAKE SCENARIO

The most recent devastating earthquake that happened in NZ was the Kaikoura earthquake with a magnitude of 7.8 Mw. It occurred in the Marlborough fault system (Duputel and Rivera, 2017) on the 14th November 2016 around 60km south-west of Kaikoura at a depth of 15km; killing two people and injuring 57. At least 14 major faults and seven minor faults ruptured with the largest surface fault offsets occurring along the Kekerengu fault (Xu et al., 2018), causing 80,000 to 100,000 landslides within an area of 10,000 km^2, five of them with more than 1,000,000 m^3 volume (Davies et al., 2017). They also reported the impact of the earthquake on transportation infrastructure, and their level-of-service, in increments up to 100 days after the impact. They determined the road level-of-service for day 1 to day 5, day 8, day 12, day 16, day 23, day 29, day 38 and day 100. As an example, Figure 6 shows the level-of-service of state highways for Day 8. State Highway 1 (SH1), the main corridor connecting Nelson, Tasman, and Marlborough regions to Christchurch city and other Canterbury districts, was completely blocked due to a number of major landslides between Ward and Mangamanua. This part of SH1 is a two-lane two-way highway with an AADT of more than 2500, of which approximately 10% are heavy vehicles. The other part of SH1 between Goose Bay and Cheviot was partially opened for emergency vehicles and residents. Two alternative routes, SH70 and Leader Road, were also closed due to the impact of the earthquake.

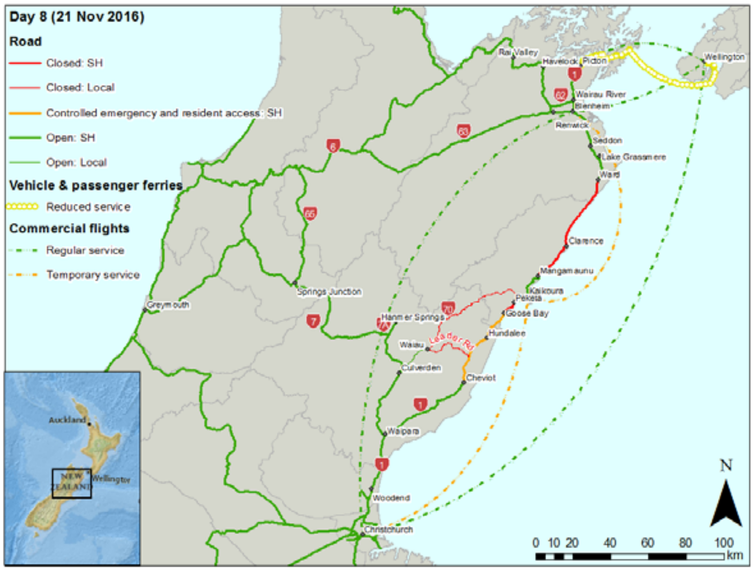


Figure 6: Road Level-of-Service Eight Days after the Kiakoura Earthquake (Davies et al., 2017)

5. VALIDATION OF THE MODEL FOR THE POST-DISASTER CONDITION

In order to perform a post-disaster validation of the model, eight days after the earthquake was selected as the scenario. By that stage, Monday 21st November 2016, travellers were assumed to have knowledge of the event and disrupted roads – this assumption is considered realistic given the coverage on traditional and social media following the earthquake. All of the post-disaster accessibility constrains in Figure 6 were applied to the model as the Day 8 scenario. It was therefore assumed that there were no trips to/from two Kaikoura traffic zones (Kaikoura Township and Kaikoura rural area), as all connecting roads were closed following the earthquake. The remainder of trips on the network were assumed to occur as per BAU. As a result, the total number of trips decreased from 640,792 to 637,101 trips, just less than 3700 trips, representing the number of eliminated trips.

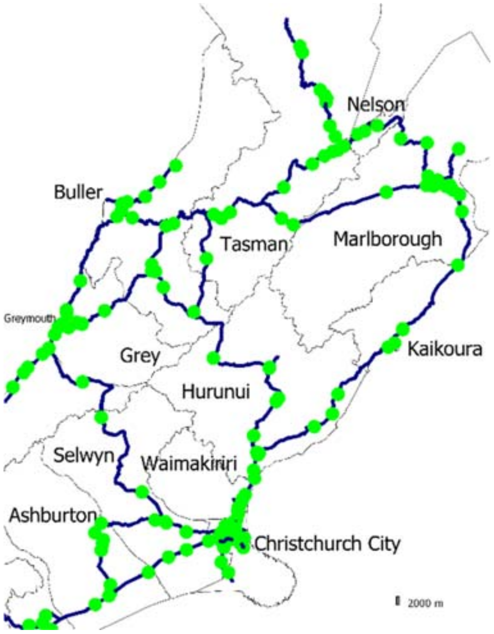


Figure 7: Detector Location on the Network Above Ashburton District

To validate the network post-disaster, the recorded 7-day ADT count data from detectors above the Ashburton District, referring to Figure 7, were extracted for a period from the 21st November 2016, eight days after the earthquake. The assumption being that no route changing happened on routes below Ashburton District given that there was no damage to routes below the this point. Figure 8 presents the validation results for all modes combined and heavy vehicles only. The R squared value and line of best fit are both at an acceptable level according to NZTA (2014) guidelines, showing that the model has been successfully validated for a post-disaster scenario. The next two sections detail the corridor and trip analysis in order to examine the network performance following the Kaikoura earthquake.

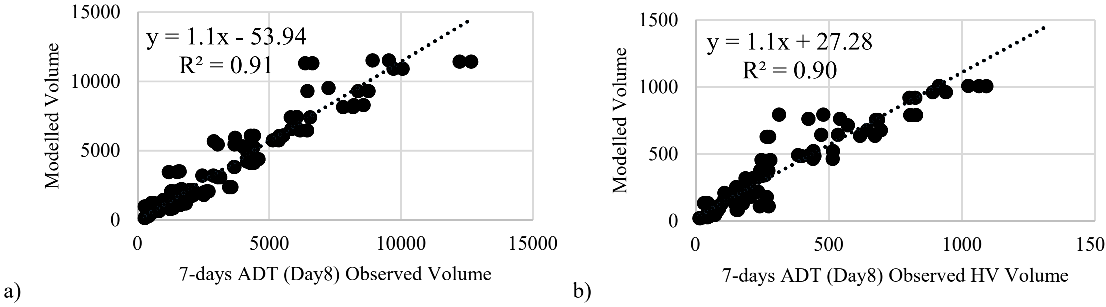


Figure 8: Validation Results Using 7-day ADT Data starting from Eight Days after the Kaikoura Earthquake a) All Modes b) HVs

6. CORRIDOR ANALYSIS

A corridor analysis was adopted in order to identify the impact of the earthquake on the performance of the network. Given that the most impacted corridors in terms of traffic count and density after the Kaikoura earthquake are located above the Ashburton District, only 21 major corridors of the main state highways were selected for further operational performance analysis. Traffic parameters of all sections on each corridor were extracted for Day 8 of the Kaikoura earthquake and compared against BAU, including average count data, average flow, sum of total travel time, sum of travel time, sum of total travelled distance, sum of delay time, and average density. The corridor analysis results are summarised in Table 3 sorted by average daily traffic count variation. What stands out is the significant influence of the earthquake on corridors connecting districts above Kaikoura (Marlborough, Nelson, and Tasman) to the districts below Kaikoura, especially Christchurch city, which was connected directly by SH1 prior to the earthquake.

Figure 9 shows the volume on the network for BAU and Day 8 after the earthquake categorised based on both colour, as per the legend, and width, where thicker network sections indicate higher volume. Focussing on the difference between Figure 9(a) and 9(b), the flow on SH1, the main pre-disaster route connecting Marlborough District to Christchurch city and other Districts south of the impacted area (Kaikoura), transferred to the shortest alternative route post-disaster resulting in an increase in journey time. The magnitude of the journey time increase being a function of the origin and destination of the trip.

According to the results, the most impacted corridors are SH65, SH63, SH6 (between SH63 and SH65), and SH7 (between SH65 and SH1). These experienced a significant variation in traffic count and density. Table 2 indicates how traffic count data varied after the Kaikoura Earthquake on these four corridors. The volume variation (%) shows an unequal significant increase among the four aforementioned corridors due to neglecting the volume weight of each corridor. By applying the volume weight on each corridor, the total volume variation (87%) is split almost equally between the four corridors. SH63, therefore, is the most impacted corridor by the Kaikoura earthquake, followed by SH6 (between SH63 and SH65). Although SH7 (between SH65 and SH1) carries the high volume of traffic, the weighted increase due to the earthquake is slightly less than other corridors (19%).

Table 2: Impact of 2016 Kaikoura Earthquake on Day 8 Traffic Count

Corridors	BAU Volume veh/day	Day 8 Volume veh/day	% Variation Compared to BAU	Weighted Variation %
SH65	521	1,398	+168%	21%
SH63	879	1,888	+115%	24%
SH6(SH63-SH65)	1,110	2,048	+85%	23%
SH7(SH65-SH1)	1,659	2,444	+47%	19%
Total	4,170	7,778	+87%	87%

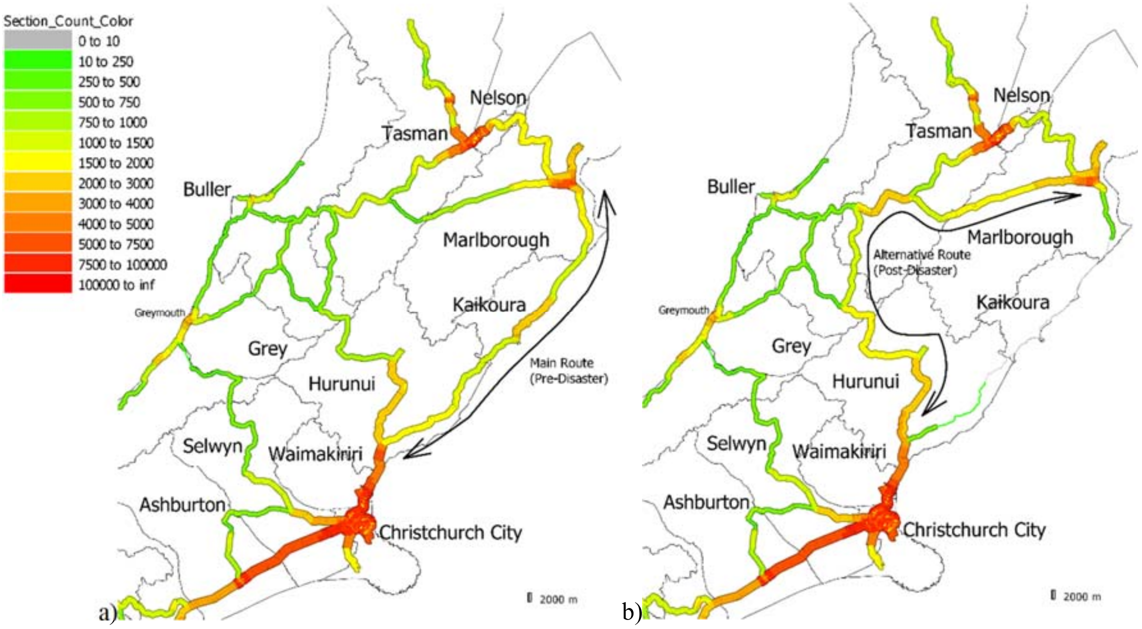


Figure 9: Volume of the Network for (a) BAU (b) Eight Days after the Kaikoura Earthquake

The rest of the corridors experienced moderate to minor flow changes, both positive and negative, as shown in Table 3. A possible explanation for this might be the reaction of the model to the route choice alteration which has been applied to the network to account for the closure of some roads. For the 2016 BAU condition, the model was set to follow the static path assignment completely. For unexpected conditions such as the Kaikoura Earthquake, vehicles cannot follow the assigned path completely due to the disruption on the network. Therefore, the path assignment option was reduced to 50%, meaning 50% of users choose the assigned path and the next 50% choose the shortest path based on travel cost. Since there is no connection on SH1 between Ward and Mangamauna, all the users of this route have to choose the alternative shortest path to complete their trips, causing a significant volume rise on the abovementioned four corridors. However, it might also cause minor to moderate changes in other corridors, as can be seen in Table 3. For corridors with reduced flow, it is more likely to be related to the demand drop due to eliminated trips to/from the two aforementioned impacted traffic zones.

While the volume on a number of corridors changed dramatically, the travel time has not been influenced significantly by the earthquake. The fact is that the volume to capacity ratio is low, even on the four most impacted corridors, therefore the impact of a dramatic rise in flow on the corridors did not have a considerable impact on travel time. It can be seen that for the first four corridors in Table 3 (highlighted ones), which experienced a significant increase in flow, mean travel time only increased by around 2%, indicating that the corridors have the ability to carry more vehicles, with no significant impact on travel time.

7. TRIP ANALYSIS

While corridor analysis investigates the impact of the earthquake on traffic parameters of each corridor, the trip analysis is a process to assess how travel time and flow varies between traffic zones. Given that the traffic zones defined for this project are in unit areas (541 traffic zones), it is difficult to analyse data at this scale. Therefore, the traffic zones were grouped into 23 districts, as shown on Figure 1, according to a StatsNZ (retrieved 2018) dataset. Tasman, Nelson, and Marlborough Regions consist of one district each. The Canterbury Region consists of nine districts, the Otago Region has five districts, and the Southland Region and West Coast Region have three districts each. As a result, the 541*541 cell matrix is converted to a 23*23 cell matrix. Analysing the aggregated traffic data from each district presents a broader perspective of the Kaikoura earthquake impact on travel time and flow among districts. The sum of total travel time and flow of all traffic zones in each district are referred to as the total travel time and flow of the district. Since total travel time is the sum of travel time experienced by all users, analysing only total travel time would cause bias and unexpected results, as the flow among traffic zones for the Day 8 scenario and BAU scenario are not the same. To reflect the impact of flow on total travel time, Equation 1 is applied to determine the average travel time variation between two districts in percentage terms. The results for the Marlborough District, the most impacted district both as an origin and destination, are illustrated in Table 4.

$$\text{TTVariation}=\frac{\frac{TotalTT_{Day8}}{Flow_{Day8}}-\frac{TotalTT_{BAU}}{Flow_{BAU}}}{\frac{TotalTT_{BAU}}{Flow_{BAU}}} \tag{1}$$

Table 3: Traffic Performance of Corridors Eight Days after the Kaikoura Earthquake

Corridors	**Volume**			**Average Travel Time (TT)**			**Average Density**		
	BAU (#)	**Day8 (#)**	**Variation (%)**	**BAU (Min)**	**Day8 (Min)**	**Variation (%)**	**BAU (Veh/km)**	**Day8 (Veh/km)**	**Variation (%)**
SH65	521	1398	168%	52.55	53.82	2.41%	0.24	0.66	172%
SH63	879	1888	115%	87.62	89.26	1.87%	0.43	0.94	118%
SH6(SH63-SH65)	1,110	2048	85%	34.77	35.37	1.72%	0.54	1.00	87%
SH7(SH65-SH1)	1,659	2444	47%	111.79	113.92	1.90%	0.78	1.16	49%
SH6(Westport-Greymouth)	674	781	16%	71.14	71.91	1.07%	0.33	0.39	17%
SH6(SH65-SH69)	550	602	9%	33.77	33.57	-0.60%	0.28	0.31	10%
SH73(SH6-SH77)	673	715	6%	133.81	134.21	0.30%	0.33	0.35	7%
SH77	649	676	4%	64.41	64.36	-0.08%	0.31	0.32	5%
SH69	675	697	3%	22.37	22.16	-0.97%	0.30	0.31	3%
SH6(SH63-Richmond)	2,460	2535	3%	55.33	54.90	-0.78%	1.12	1.15	3%
SH6(SH69-Westport)	487	499	2%	32.63	32.70	0.20%	0.26	0.27	3%
SH6(SH73-Wanaka)	730	745	2%	325.96	325.74	-0.07%	0.36	0.37	2%
SH1(SH76-SH77)	8,501	8424	-1%	51.17	51.14	-0.06%	3.63	3.57	-2%
SH7(SH69-SH65)	425	399	-6%	32.59	32.30	-0.90%	0.21	0.19	-7%
SH60	2,700	2520	-7%	95.01	94.57	-0.46%	1.42	1.32	-7%
SH1(SH7-SH71)	5,988	5445	-9%	27.30	27.26	-0.15%	2.99	2.71	-9%
SH6(Havelock-SH62)	1,719	1555	-10%	17.58	17.36	-1.28%	0.81	0.72	-11%
SH6(Nelson-Havelock)	2,324	2063	-11%	58.48	58.09	-0.67%	1.22	1.08	-12%
SH7(SH6-SH69)	851	734	-14%	53.46	52.58	-1.65%	0.38	0.33	-15%
SH6(SH7-SH73)	3,046	2625	-14%	16.00	15.91	-0.57%	1.92	1.62	-16%
SH73(SH77-SH1)	3,398	2919	-14%	24.14	23.48	-2.75%	1.52	1.24	-19%

The result shows that average travel time from traffic zones in Marlborough District to traffic zones in Christchurch City, for example, increased by 46%, which is primarily due to the increase in average travelled distance of 139km (41%), as detailed in Table 4. Average travel time to districts located south of Kaikoura, such as Ashburton, Hurunui, Selwyn, Timaru, Waimakariri, Dunedin, and Christchurch city, from Marlborough District increased by around 20% to 90%, depending on the increase in travelled distance. Trips to Hurunui District, the closest district to the impacted area (Kaikoura), experienced a significant increase in average travel time, 90%, where the shortest post-disaster path increased by 186km (78%). It can be seen that there is a direct relationship between the increase in average travelled distance and the increase in average travel time eight days after the Kaikoura Earthquake, where the travelled distance increased by 148km on average resulting in increased travel time of 123 minutes on average.

A sensitivity analysis was undertaken to evaluate the impact of increase in traffic demand (by 10% and 20%) on the average travel time. This showed negligible growth in average travel time, indicating low sensitivity to the demand rise. This was expected as the Volume/Capacity ratio on these corridors is low and no congested areas were identified due to the re-routing and increased demand.

Table 4: Travel Time and Travelled Distance Variation from Marlborough Eight Days after the Kaikoura Earthquake

Districts	Ave. BAU Travelled Distance (km)	Ave. Day8 Travelled Distance (km)	Day8 Variation (km, %)	Ave. BAU Travel Time (min)	Ave. Day8 Travel Time (min)	Day8 Variation (min, %)
Hurunui	237	423	186(78%)	172	326	154(90%)
Waimakariri	302	436	134(44%)	229	338	109(48%)
Christchurch	341	480	139(41%)	254	370	116(46%)
Selwyn	360	505	145(40%)	269	388	119(44%)
Timaru	477	633	156(33%)	355	495	140(39%)
Ashburton	421	561	140(33%)	313	422	109(35%)
Dunedin	697	836	139(20%)	535	646	112(21%)

8. CONCLUSION

The 2016 Kaikoura earthquake, a 7.8 (Mw) magnitude event, occurred two minutes after midnight on 14th November 2016 NZDT, around 60km south-west of Kaikoura at a depth of 15km. The earthquake caused numerous landslides, many of them were significant, resulting in widespread disruption to SH1 of the South Island's road network following the earthquake using a mesoscopic traffic simulation model of the South Island's road network. The model, developed in Aimsun, was validated, first, against BAU 2016 AADT data, and then, against 7-day ADT data starting from Day 8 after the Kaikoura earthquake. Corridor analysis and trip analysis were conducted to assess post-disaster operational performance of the road network. The main findings of this research are as follows:

- The validation of the network was undertaken for a post-disaster situation, Day 8 after the Kaikoura earthquake, to help quantify the reliability of the simulation outcomes and, therefore, decrease the degree of uncertainty associated with travel demand behaviour in a post-disaster scenario. It was assumed that users had knowledge of the event and disrupted roads by Day 8 – this assumption is considered realistic given the coverage on traditional and social media following the earthquake. The resulting R squared value and best line of fit were at an acceptable level. It can therefore be concluded that the model was successfully validated, confirming it can be used by Civil Defence and Emergency Management and other organisations to predict, and thereby plan for, disruptions caused by any future earthquakes and by extension, albeit with reduced confidence, to other natural or man-made incidents.

- While the performance of different transportation assets after the Kaikoura earthquake were assessed previously, the impact of the event on corridors and travellers has not been undertaken to date. The post-disaster operational performance of the network, therefore, was analysed based on 21 selected corridors among State Highways using traffic count, density, and travel time. The results indicate a significant rise in traffic count and density on four main corridors which, in combination, operated as the main alternative route after the earthquake, namely: SH65, SH63, SH6 (between SH63 and 65), and SH7 (between SH65 and SH1). These corridors connect Marlborough traffic zones, north of Kaikoura, to Christchurch and other main traffic zones south of Kaikoura. Average speeds along the corridors decreased slightly due to the increased traffic volumes, however, as the volume to capacity ratio is reasonably low on these corridors, none of the corridors experienced congestion during re-routing. Density increased at a similar rate to the volume rate.

- Finally, understanding the impact of the event on traveller's journey time is a key part of the post-disaster trip analysis. The results showed significant travel time increases, typically 20-50%, from Marlborough to other affected districts with the worst reported being a 90% increase. The result shows that travel time from traffic zones in Marlborough to traffic zones in Christchurch, for instance, increased from an of average 4:15 hours to 6:10 hours, a 46% increase. Such information allows for the calculation of the economic impact of the Kaikoura earthquake, in terms of increased vehicle operating costs and travel time costs, by comparing the pre- and post-disaster scenarios.

Now that the model has been validated in a post-disaster environment, future research will predict the performance of the South Island road network following a potential future Alpine Fault Magnitude 8 (AF8) earthquake strike. A future Alpine Fault earthquake is of real concern with the next large earthquake on the Alpine Fault likely to occur within our, or our children's, lifetime.

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