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Inter-regional movement and contagion risk analysis August 2021

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EXECUTIVE SUMMARY

We use a range of data sources and analytic approaches to estimate the number of movements between regions of Aotearoa and to give some estimates of the risk of transmission of COVID-19 to regions outside of Auckland, during the early stages of the August 2021 outbreak.
We also use one of these approaches — the *Aotearoa Co-incidence Network* — to generate some regional boundaries that are optimal for preventing inter-regional spread of COVID-19, in the sense that they partition the country into regions that minimise the potential spread *between* regions while maximising the number of links that are allowed to remain *within* regions.
We find that:

- The regions at greatest risk of onward transmission from Auckland, in the period before 17th August, 2021 were **Hamilton, Wellington, and Christchurch and their surrounding Territorial Authorities (TAs) along with Queenstown Lakes**.

- The movement based risk assessment does not account for current epidemiological evidence, i.e. confirmed cases of COVID-19 in Wellington, but not in e.g. Christchurch.

- Other than a brief initial surge of travel north from Auckland on August 17th, there are **very low levels of vehicle movements in or out of Auckland during the current AL4 intervention** - similar to previous elevated alert levels. Similarly, traffic movements within Auckland are reduced to those seen in previous periods at AL4.

- Potential interactions through work or education, in the period prior to August 17th, **for individuals living in those SA2s where cases of COVID-19 had been confirmed by August 21st extend beyond the Auckland region**. Within Auckland, the pattern of SA2s with large numbers of potential interactions is heterogeneous and is widely spread, spatially.

- It is possible to partition the country into regions with high numbers of connections through work or education within the region and low numbers of interaction between regions. Some possible partitionings are presented.

1 Introduction

In the absence of real-time movement and interaction data, a number of surrogate data sources can be used to infer the chance of an appreciable number of movements between a pair of regions, or the number of interactions that might lead to COVID-19 transmission. These include using historical data that might be broadly representative of a more recent period. Here we use data from three sources: i) spatial data at the level of Statistical Area 2 (SA2) to Territorial Authority (TA) movements inferred from aggregated weekly 2019 and 2020 electronic transaction data; ii) counts of traffic movements at highway monitoring points for both recent and historic flows; and iii) spatial data for inferred relative numbers of potential interactions with individuals other regions, based on aggregated microdata for Census 2018 linked to Inland Revenue employment information.

2 Electronic Transaction Data

We use electronic transaction data to derive movement patterns, to and from Auckland, over 2019 and 2020 with a focus in the movements in week 32 - the week preceding the Auckland August outbreak in 2020. These historical movement patterns are likely to be a good proxy for inter-regional travel to and from Auckland, immediately prior to the August 2021 COVID-19 outbreak. Movements are derived from a data set of credit card spend data that was purchased from Marketview. This dataset was produced by Marketview from BNZ card transactions, excluding online transactions where a card was not physically presented.

In particular, we summarise both the movements *going to* the Auckland TA from other TAs, as well as those *travelling from* Auckland to other TAs.

The data that Marketview[*] uses comes from individual transaction information for active BNZ credit card holders across New Zealand. From this data we can investigate how individuals move across NZ, by looking at the aggregated spending patterns linking customers' "home" locations, and the locations of the merchants where money is spent. This is one of the few data sources that has a well defined home location for people, allowing us to identify precise long-range, or inter-regional, movements.

Marketview provided a feed of these aggregated data covering the period January 2019 to November 2020. This range of data allows for an observation of the impact of COVID-19 on spending patterns (and thus movement patterns) in 2020, with comparison to "normal" patterns observed in 2019.

The period covered by this data does not extend to 2021. However, it does include a period in 2020 with what we believe to be very similar circumstances to the period of interest in 2021. The Auckland August outbreak of 2020 occurred at almost the same point in the year at the 2021 outbreak (in both cases, the week immediately preceding detection was week 32) including, significantly, the timing with respect to school and university holidays. We have therefore used the equivalent weeks of 2020 (before and after Auckland moved to Alert Level 3, and the rest of Aotearoa moved to Alert Level 2, on 12 August 2020) as a proxy for the expected movement patterns around the time of the August 2021 outbreak.

It is worth noting that, like all data, the electronic transaction data from Marketview is likely to be affected by some degree of participant bias. For example, it is to be expected that lower income New Zealanders could be less likely to have, or to use a credit card and hence the movements captured in this data my be skewed to those of more affluent New Zealanders. As discussed in section 2.1, Marketview employ an in-house re-weighting method to scale the population of credit card holders up to a representative NZ population. From our conversations with Marketview analysts, it appears unlikely that that their re-weighting adjusts for this participant bias.

2.1 Method

Marketview derives a home location based on the geographical location of each individual's address, as recorded by BNZ. For each transaction made, Marketview records the merchant's location and the transaction time.

Before we are provided with the data, each customer's home location is aggregated by Marketview to a total count for each 2018 level 2 statistical area (SA2)[†]. Merchant locations are similarly aggregated to the level of 2018 Territorial Authority (TA)[‡].

A number of processing steps were undertaken by Marketview before providing the data. From the records of spending each week, Marketview first identifies all spends outside a customer's home location (TA) in a given week. Marketview then applies a number of logic rules to create "trips", using information about dates with no spending, or dates with spending back in the home location, to estimate the length of a trip.

There are some important limitations and caveats to this data. Firstly, because the data is broken down by week, spending on a consecutive Saturday, Sunday, and Monday in a given location would be considered a 2 day trip in the first week and a

[*] http://marketview.co.nz

[†] https://datafinder.stats.govt.nz/layer/92212-statistical-area-2-2018-generalised/

[‡] https://datafinder.stats.govt.nz/layer/92214-territorial-authority-2018-generalised/

1 day trip in the next. Furthermore, because we are interested in the different locations a person visits (and potentially has an infection transmission interaction in), if a customer spent money in two different locations (TAs) on the same day, this is considered two trips, one to each location. Finally, and most importantly, for the data to provide a generalisable representation of the New Zealand population, Marketview scale the counts obtained for BNZ cardholders up the StatsNZ estimated resident population (aged 15+) according to a number of demographic factors. There are a number of internal proprietary steps in this re-scaling, which mean that the effective total population recreated can vary week-to-week, especially in small SA2s. One specific issue that we have identified with the Marketview process is that the re-scaling algorithm is unstable for those SA2s with only a small number of BNZ cardholders. As an extreme example, this would mean that if an SA2 contained only 1 BNZ cardholder, with any type of spending behaviour, that 1 cardholder would be up-weighted to represent the entire population of that SA2. In the analysis presented here, we have aggregated multiple origin SA2s into their larger TA units. This is expected to mostly mitigate the effects of small population fluctuations.

2.2 Results

2.2.1 Trips into Auckland

We have estimated the number of trips *to* Auckland for each week, from January 2019 to November 2020. Travel in 2019 provides a useful comparison of the number and pattern of trips week-to-week, in a normal year. Details of how the data was aggregated by Marketview means it is possible to determine the number of *trips* to a location in a given week, but not the number of *distinct visitors*. For example, 5 trips in a week could represent 5 trips from the same person, who returns to their home location between each of them, or 5 trips from from different people. There will be minor differences between the contagion risk of these two scenarios (and for trips of longer vs shorter duration), however, to first order, we expect these two measures to be comparable in terms of risk.

The typical week, in a typical (pre-COVID) year, sees about 150,000 trips to Auckland, with the fist week of the year being a notable exception. In Figure 1 below, weeks are colour coded by the Alert Level that was in place at that time. The reduction of visits to Auckland due to COVID-19 Alert Levels in 2020 is easily seen. During periods of 2020 when Aotearoa was at AL1, there were typically 100,000 visits to Auckland, per week. This dropped to around 50,000 in August 2020 when Auckland was at AL3 and the rest of NZ was at AL2. As a comparison, when all of Aotearoa was at AL4 in April 2020, there were still approximately 25,000 trips to Auckland per week.

Based on this, **we would estimate that in the week prior to August 17th, 2021, there were around 115,000 visits to Auckland from people in other regions**.

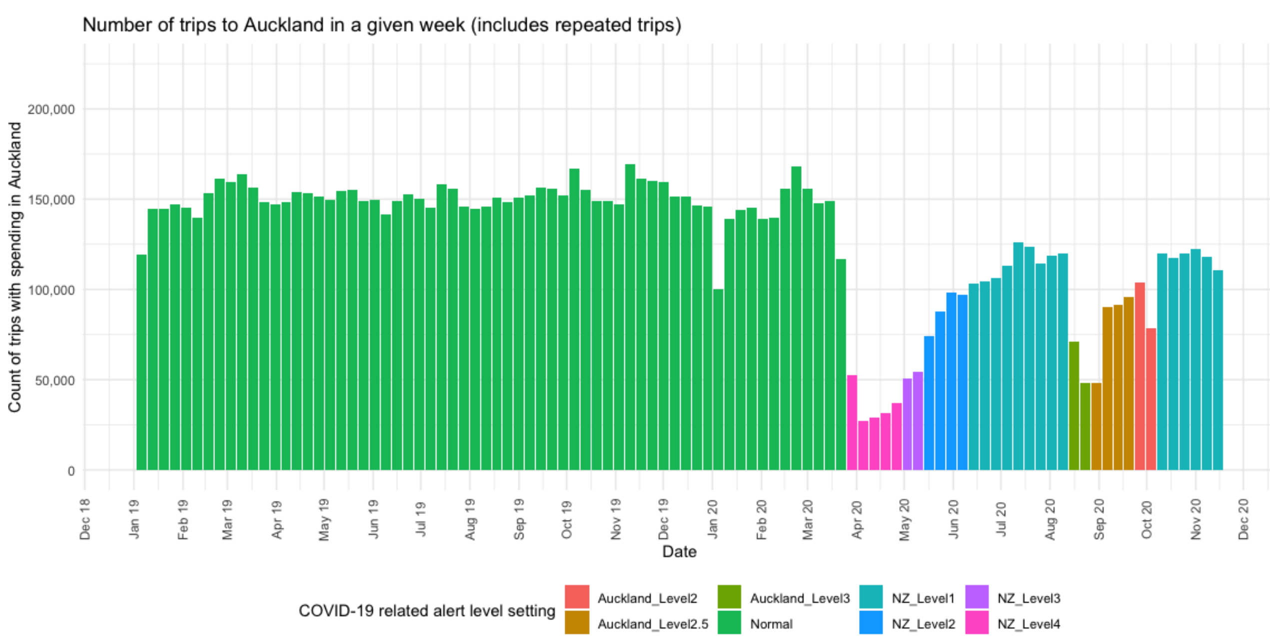

Figure 1. Trips to Auckland, per week, from travellers with a home outside of the Auckland region, for the period January 2019 to November 2020. Before the arrival of COVID-19 in Aotearoa there were around 150,000 trips to Auckland each week. During 2020, in periods when the country was at Alert Level 1, Auckland was the destination for 100,000–125,000 trips per week.

2.2.2 Distinct Travellers out of Auckland

For trips *leaving* a specified region, we are able to calculate the number of *distinct travelers* who are estimated to have visited areas outside their home TA (or SA2) in a given week. These are plotted in Figure 2 below. Data from 2019 shows that, in a typical year, trips out of Auckland are highly seasonal; public holidays and school holidays are easily identified. In a week with no boosting from holiday effects, there were typically just over 100,000 distinct travelers who left Auckland to visit one or more other regions. During early 2020, when all of Aotearoa was at AL4, the number of people traveling outside of Auckland fell to around 35,000 per week. In the weeks preceding the 2020 Auckland August outbreak, and excluding school holiday weeks, there were typically around 130,000 distinct people leaving Auckland, per week. It is interesting to note that in the period when Auckland was at AL2.5, Aucklanders returned to this same level of travel as during AL1.

Based on this, we would **estimate that in the week preceding August 17th, 2021, there were around 130,000 Aucklanders who traveled** to one or more regions outside of the Auckland TA.

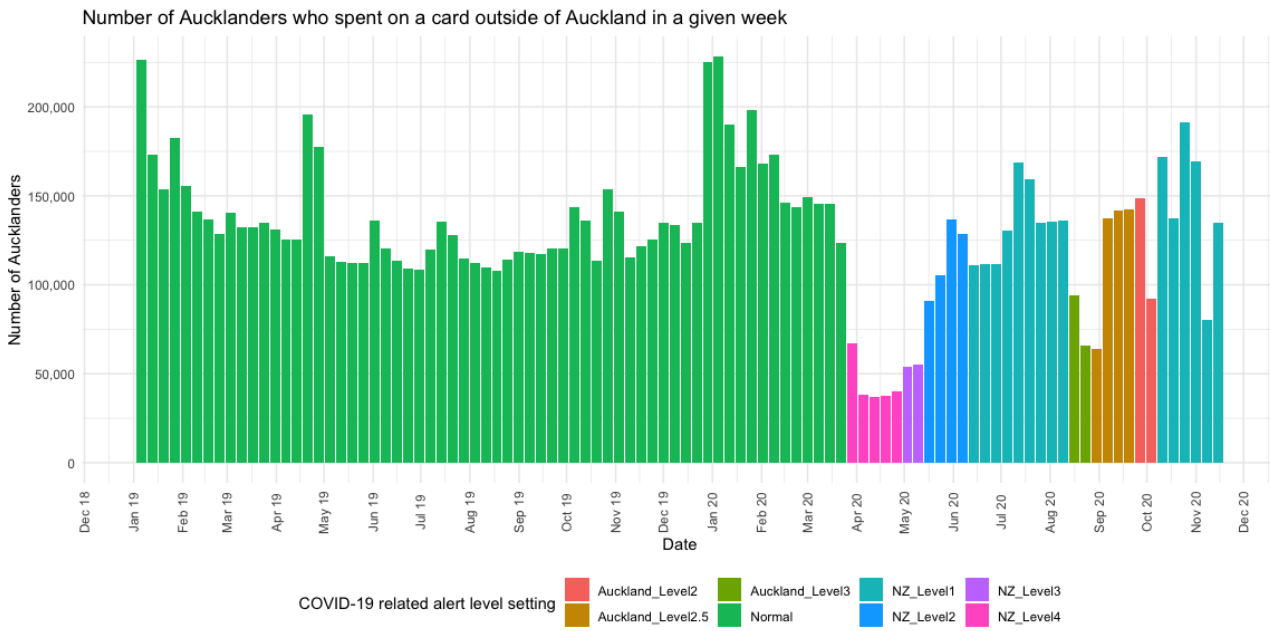

Figure 2. Counts, per week, of distinct travelers from Auckland, to other regions of Aotearoa. In the weeks preceding the 2020 Auckland August outbreak, around 130,000 distinct travelers per week made trips outside of the Auckland region.

2.2.3 Origin and Destination of Travel Involving Auckland

In order to identify which locations were at highest risk of forward transmission, during the period of detected community spread of COVID, *prior to August 17th 2021*, we can look at the origin and destination of travelers to and from Auckland. The charts below show the number of *trips* to (respectively, from) Auckland in the week immediately prior to the Auckland August outbreak of 2020, and for the equivalent week in 2019. These are plotted for every potential origin (resp. destination) TA.

The origin of most trips *to Auckland* were broadly similar in 2019 and 2020. As identified above, there were slightly fewer trips to Auckland in week 32 of 2020 (the week preceding detection of the Auckland August outbreak), compared with week 32 of 2019. Visits to Auckland were dominated strongly by visit from other cities with proximity to Auckland and population being clear driving factors.

Based on these, in the week preceding 17th August, 2021 we would expect that the **significant origins of visitors to Auckland** were, in approximate order:

- Hamilton TA (12k);
- Christchurch (10k);
- Wellington (9k);
- Whangarei (9k);
- Tauranga (6k);

- Waikato TA (6k);
- Kaipara (5k);
- Far North (5k);
- Dunedin (5k).

The *destination of trips from Auckland* in week 32 shows a distinctly different pattern to the origins. It also shows a significant change in travel behaviour from 2019 to 2020 for travel to Queenstown Lakes — this is one of only three regions (the others are Thames-Coromandel and Taupō) to show a marked *increase* in trips, increasing from just under 10,000 trips in week 32 of 2019 to around 17,000 trips in week 32 of 2020.

Based on these, in the week preceding 17th August, 2021 we would expect that the **significant destinations of visitors from Auckland** were, in approximate order:

- Queenstown Lakes (17k);
- Wellington (16k);
- Hamilton TA (15k);
- Tauranga (14k);
- Christchurch (14k);
- Thames-Coromandel (12k);
- Whangarei (10k);
- Taupō (10k);
- Far North (8k);
- Waikato TA (8k);
- Kaipara (7k);
- Dunedin (6k);
- Rotorua (6k).

N.B. It is worth noting that with respect to movements to and from the Waikato/Hamilton region, TAs are split as Hamilton, Waikato, Matamata-Piako, etc. Together these comprise a region with a large number of movements that could be captured as Hamilton + surrounds.

Origin of Travelers Linked to Auckland Via Other Regions

The Queenstown Lakes region had high numbers of visitors from other regions in Aotearoa over periods of lower Alert Levels in 2020. The region is distinctive in that is has high numbers of non-reciprocated visits with Auckland. That is, data from a similar period in August 2020 suggests that, in the week prior to August 17th, 2021 there were a large number of travelers from Auckland, who visited Queenstown Lakes, but only low numbers of visitors from the Queesntown Lakes region to Auckland. This makes the region a particular location of interest, with respect to the origins of travelers to Queenstown Lakes from other regions in Aotearoa, in the case of a possible visit by an infectious traveler from Auckland during the week preceding August 17th, 2021. Figure 3 shows the origins and numbers of travelers to the Queenstown Lakes region in week 32 of 2020.

Of the approximately 60,000 trips to Queenstown Lakes in the week preceding the 2020 Auckland August outbreak, travelers from Auckland were by far the biggest single source with 15,000 trips (25%). Other significant origins were:

- Christchurch (5k);
- Dunedin (4k);
- Wellington (3k);

- Central Otago (2.5k);
- Invercargill (2k).

With the exception of travelers from Wellington, where COVID-19 has already been confirmed, **the majority of travelers who could have interacted with a traveler from Auckland in the Queenstown Lakes region are from geographically close areas in the lower South Island.**

We repeat the analysis above for Wellington and Christchurch, the two other significant destinations for travelers from Auckland in the week preceding the discovery of the outbreak. Results are shown in Figures 4 and 5. For Wellington and Christchurch, the origin of travelers from regions other than Auckland is strongly dominated by travel from neighbouring TAs. That is, Waimakareirei, Selwyn, Hurunui, Ashburton, and Timaru for Christchurch; and Kapiti Coast, Porirua, and Lower and Upper Hutt for Wellington, with the addition of regional centres Christchurch, Dunedin, and Plamerston North. As context, these latter cities each represent 5000 or fewer trips per week, compared with 15,000 from Auckland or 10,000 from Kapiti Coast.

3 Traffic Movements

Measurements of vehicle movements are a potentially useful way of estimating both intra- and inter-regional travel. This data can take the form of point counts from Remote Traffic Monitoring (RTM) sites, such as those operated by Waka Kotahi - the New Zealand Transport Agency (NZTA) on state highways. Alternatively, estimates of vehicle movements can be inferred from aggregated navigation information from mobile devices, such as mobility data from Apple and Google. Data from RTM measurements is limited in that it is only collected at a small number of fixed points, but it is able to provide an absolute count of vehicle movements at that point. In contrast, navigation based mobility data can provide an estimate of movements over an entire region or country but only as a relative reduction, and with a number of potential biases related to who is using such services and for which trips.

3.1 Method

RTM data was obtained from the NZTA Traffic Monitoring System (TMS) API[1], which contains daily traffic counts from telemetry sites across Aotearoa New Zealand. We focus on telemetry sites located in Auckland, drawing upon data from different time periods from 2020 to 2021. The Wellsford and Bombay sites are of particular interest as they represent main routes out of Auckland on SH1 to the North and South respectively.

Data is available from https://opendata-nzta.opendata.arcgis.com/datasets/tms-daily-traffic-counts-api/explore?showTable=true . The PDF in this directory shows the location of all telemetry sites nationwide.

We also used Apple Mobility Data[2] for Aotearoa. This data shows the change in the number of requests for navigation directions, from the whole of the country, and for the Auckland region, relative to a baseline of January 13th, 2020.

3.2 Results

3.2.1 NZTA highway measurements

Traffic counts for light (ie mostly non-commercial) vehicles at the Wellsford and Bombay RTM sites are shown in Figures 6 and 7 for the 7 days leading up to a lockdown, and the 20 subsequent days (or if it came before 20 days, the end of the lockdown). ‘Day 0’ is defined as the first day fully or partially spent under heightened alert levels; in cases where restrictions began at 11:59 pm, the following day is Day 0. In all other cases, the day restrictions began is Day 0.

Data is shown for four periods of elevated alert levels — those beginning in: March 2020; August 2020; February 2021; and August 2021. It is worth noting that in February 2021, Auckland had a brief period at AL3, followed by period of 10 days at AL2, before returning to AL3. The intermediate period when Auckland was at AL2 is indicated by the shaded regions on the figures below.

Recent periods of elevated alert levels have been associated with an increase in traffic flows in the hours between when the intervention was announced and when it came in to place. This seen as an increase in traffic flows north from Auckland on Tuesday 17th August 2021 with traffic counts similar to those seen on a Friday — an increase of around 30% above typical movements. (In contrast, the announcement of AL3 for Auckland in February 2021 saw, in addition to an exodus north, an influx of travellers returning to Auckland — presumably ending summer holidays.) Once heightened alert levels are in place, both AL3 and AL4 interventions show comparable reductions in vehicle movements in and out of the Auckland region, at both Bombay and Wellsford. The current (up to 22/08/2021) data show that movements through these sites are very similar to those seen during previous period at AL3 and AL4 (other than February 2021 due to the fluctuation in alert levels).

Southbound traffic through Bombay the day before the most recent AL4 came into effect appears no higher than usual, suggesting people were not leaving Auckland to the South at the same rates as they left to the North. In past lockdowns, there

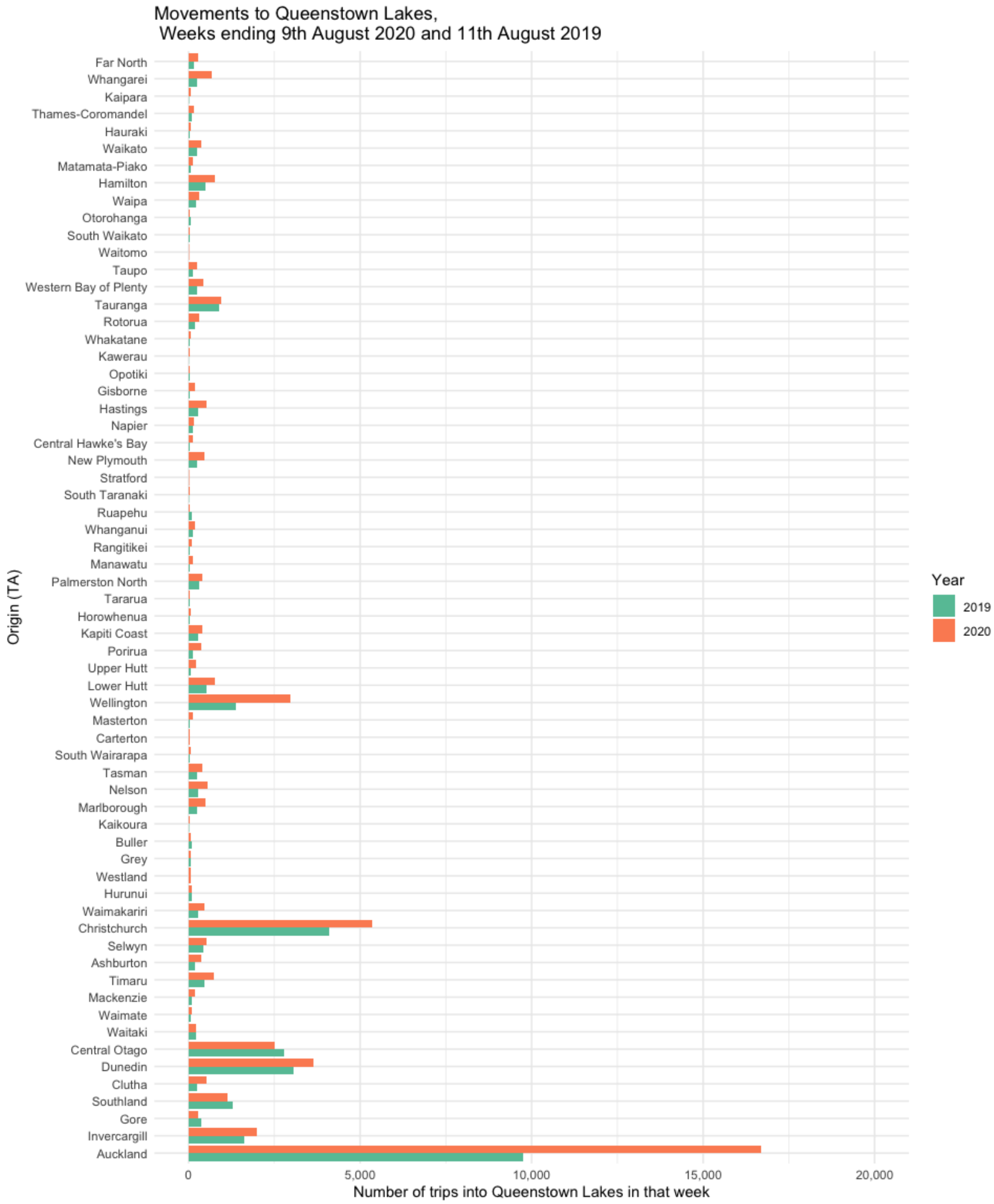

Figure 3. Counts and origins of traveler to Queenstown Lakes region in week 32 of 2020. Other than Auckland, and with the exception of Wellington where COVID-19 has already been confirmed, the majority of travelers who could have interacted with an infected visitor from Auckland were from surrounding areas in the lower South Island.

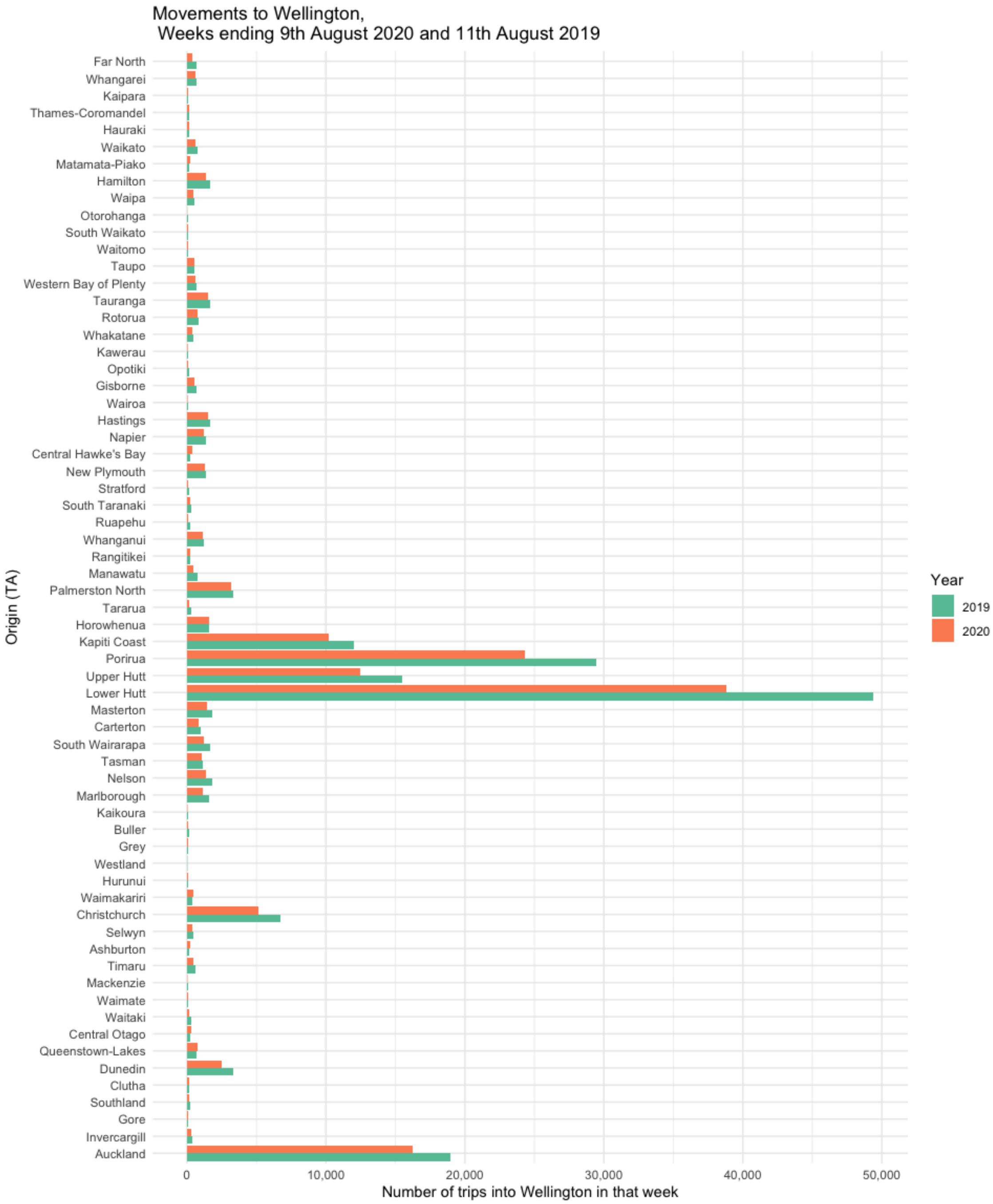

Figure 4. Counts and origins of travellers to Wellington in week 32 of 2020. With the exception of Auckland, travel to the Wellington TA is from TAs in the surrounding areas. Other contributions come from regional centres — Christchurch, Palmerston North, and Dunedin.

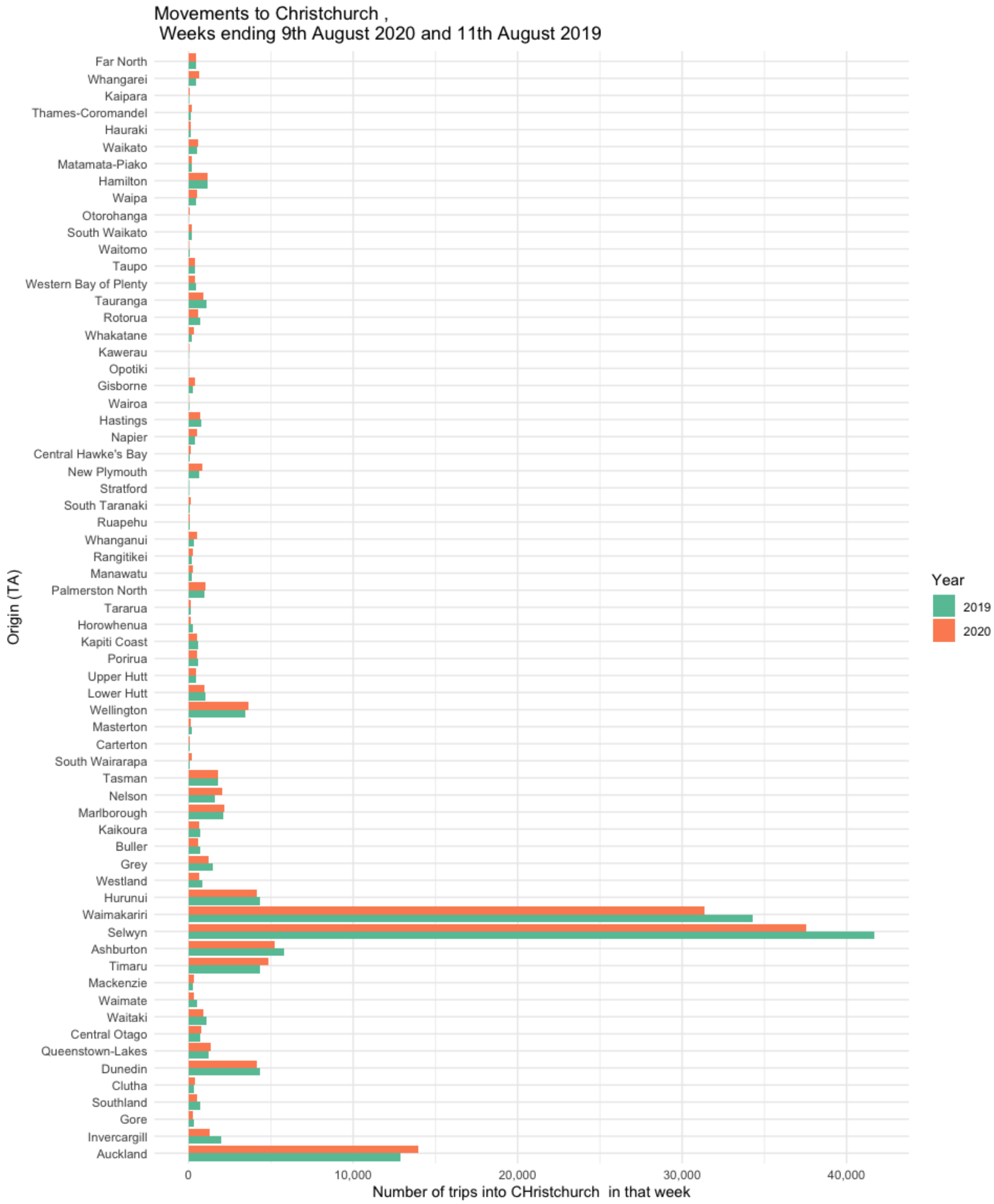

Figure 5. Counts and origins of travellers to Christchurch in week 32 of 2020. The origins of travel to the Christchurch TA are strongly dominated by the surrounding TAs, with the exception of travel from Auckland, and to a much lesser extent, Dunedin and Wellington.

has been an increase in southbound traffic through Bombay. The absence of a clear southern exodus for the most ecent AL4 announcement could possibly be attributed to early locations of interest being announced in the Coromandel, resulting in fewer people attempting to leave Auckland for the Coromandel.

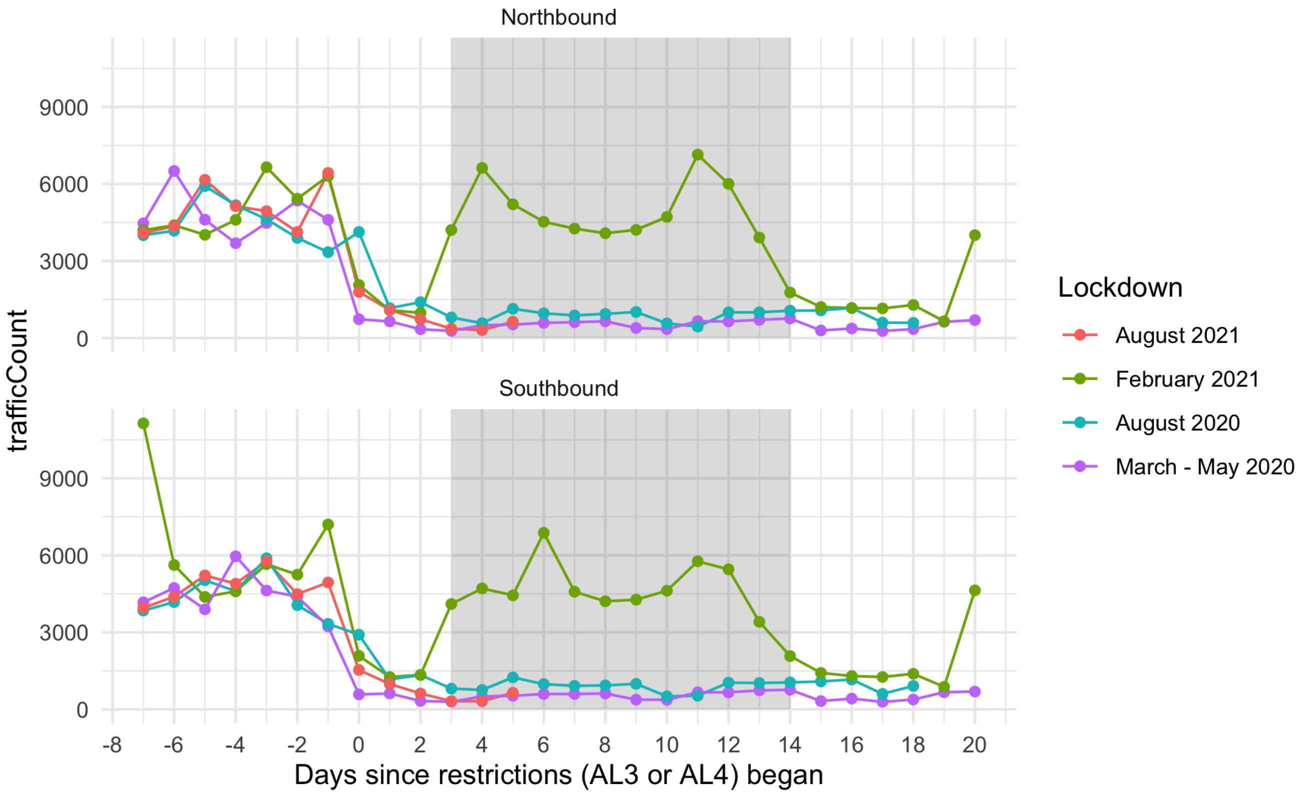

Figure 6. Wellsford Traffic Flow. The above plot shows the traffic flow count for journeys heading northbound and southbound through the Wellsford telemetry site. The shaded grey area indicates the period during February 2021 when Auckland moved to AL2 and subsequently AL1 before returning to AL3 on February 28th.

3.2.2 Apple Mobility Data

As a comparison to the telemetry and Marketview data, direction request data from Apple was analysed. Apple mobility data for driving in New Zealand and the Auckland Region are shown in Figures 8 and 9. These figures show the percentage change in requests for Apple map directions, compared to a January 13th, 2020 baseline, for each day from 2020 to August 24th 2021. In both cases the intervention of Alert Level 4 results in a reduction of estimated movements of around 75%, relative to the January 13th, 2020 baseline. The estimated driving reduction in Alert Level 4 for the August 2021 outbreak is, however, around 10% less than that observed in March/April 2020.

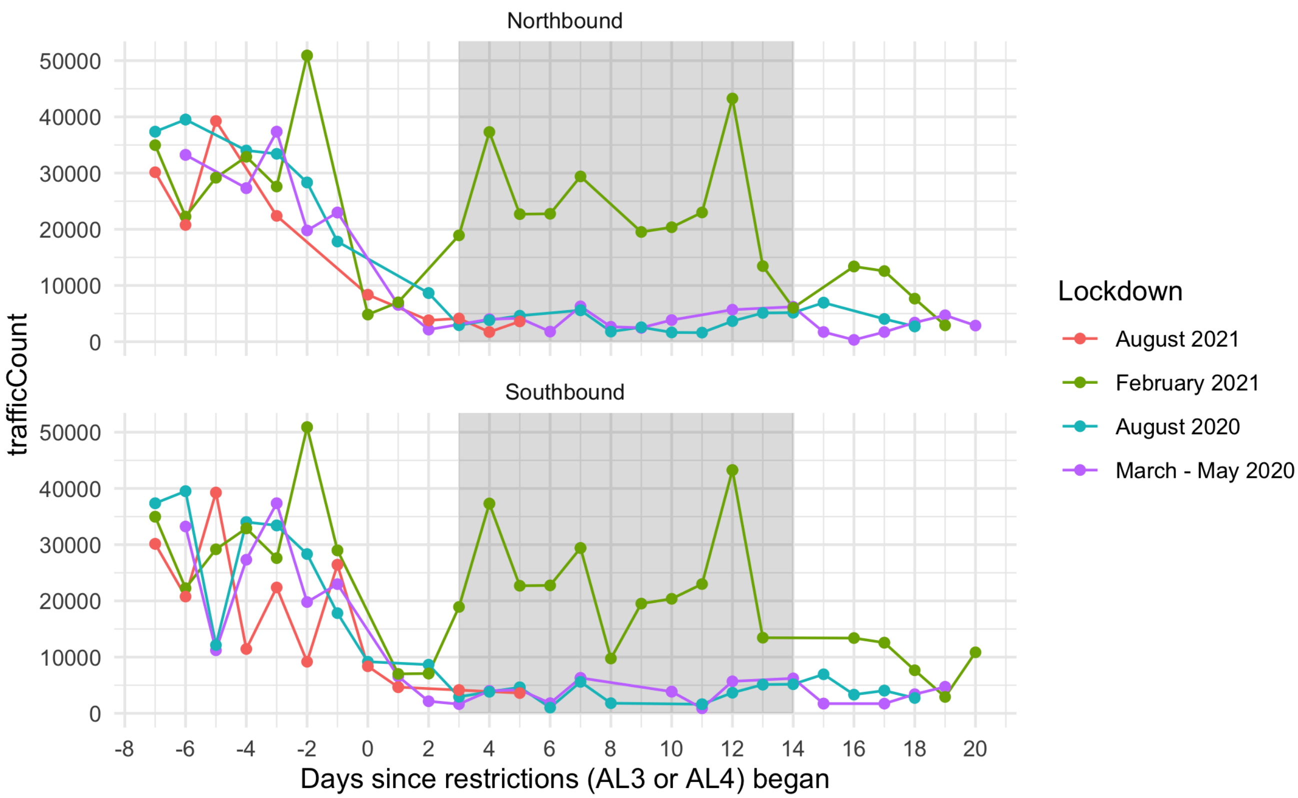

Figure 7. Bombay Traffic Flow. The above plot shows the traffic flow count for journeys heading northbound and southbound through the Bombay telemetry site. The shaded grey area indicates the period during February 2021 when Auckland moved to AL2 and subsequently AL1 before returning to AL3 on February 28th.

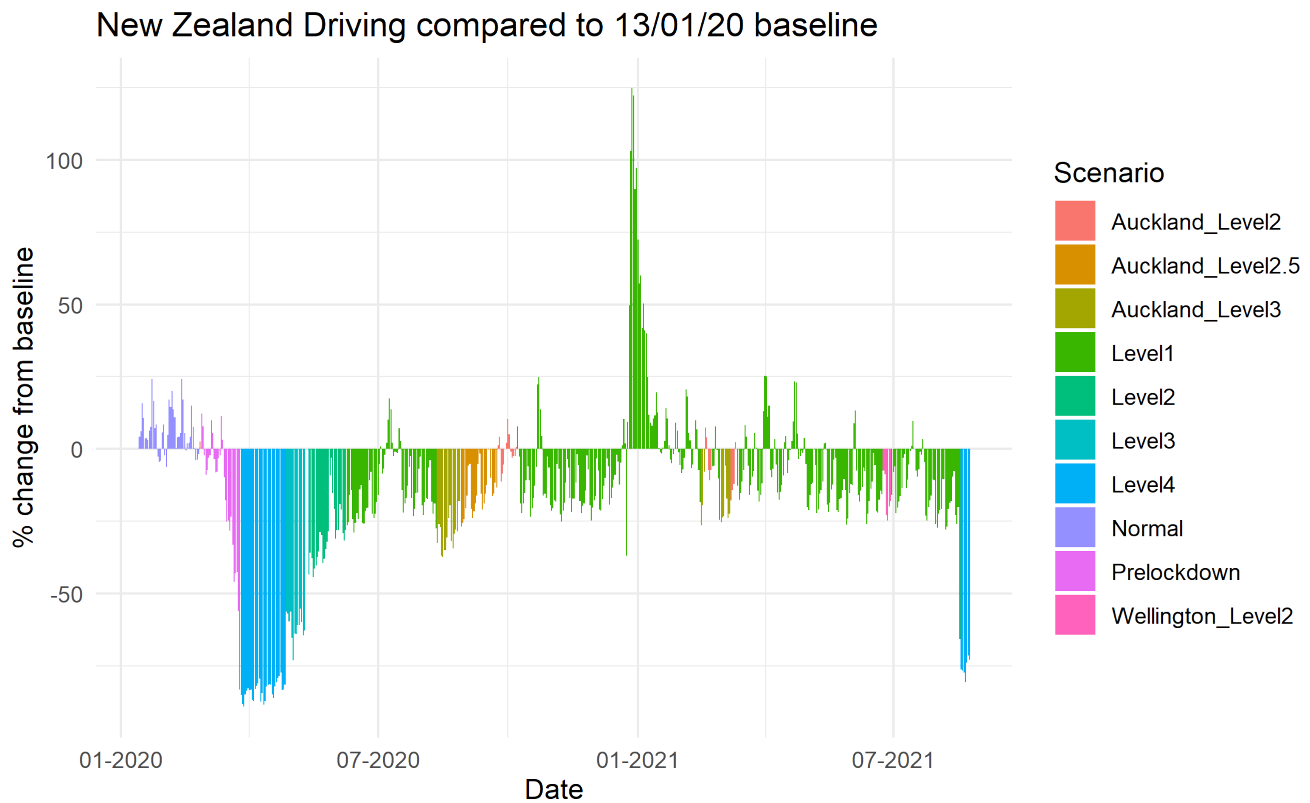

Figure 8. New Zealand Apple mobility data shows that the AL4 lockdown in March - May 2020 led to a 9% greater decrease in direction requests than AL4 lockdown in August 2021. The different Alert Level scenarios correspond to different colourings of the bars.

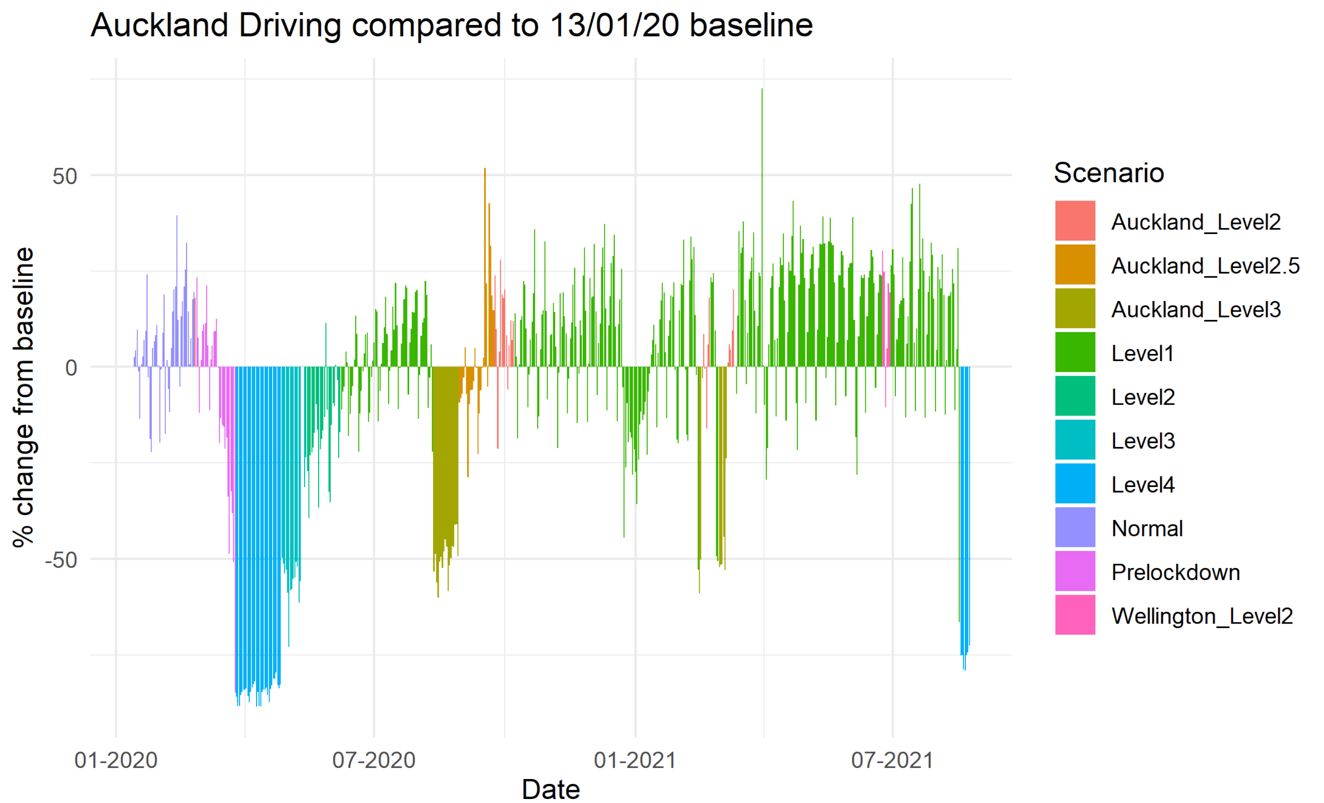

Figure 9. Auckland Apple mobility data shows that the AL4 lockdown in March - May 2020 led to an 8% greater decrease in direction requests than AL4 lockdown in August 2021. The different Alert Level scenarios correspond to different colourings of the bars.

In terms of direction requests, both the New Zealand (see Figure 8) and Auckland Region (see Figure 9) show that the AL4 period of March-May 2020 had an almost 10% greater initial effect (relative to the January 13th, 2020 baseline) than the introduction of AL4 in August 2021. In contrast to the NZTA RTM data which showed that historically, AL3 (applied to Auckland only) and AL4 (applied nationally) had similar effects in reducing vehicle movements in and out of Auckland; the AL4 periods in March-May 2020 and August 2021 had a 40-50% greater impact at a national level than the AL3 lockdown in August 2020.

4 The Aotearoa Co-incidence Network: Application to Regional Spread

The Aotearoa Co-incidence Network (ACN) is formed from the connections induced by interactions between individuals from dwellings in different regions of Aotearoa. The ACN details the number of connections made through shared workplaces and schools, which gives an indication of likely transmission spread should an outbreak of COVID-19 occur. The ACN makes no assumptions about the likely point of occurrence for an initial outbreak. That is,the transmission risk represented is an estimate of the risk of onward transmission to a region, for an initial outbreak that occurs at an *arbitrary* location in the country. Clearly, some regions (e.g. those with MIQ facilities and international airports) are at higher risk of being locations for seeding an outbreak. In contrast to the electronic transaction data which was useful for identifying long-range, inter-regional links, the ACN is useful for revealing shorter-range links associated to the day-to-day movements of individuals and those of the people that they interact with through work and education. It also offers a finer-grained spatial analysis at the level of SA2s within cites and regions.

Here we apply the ACN to the question of: *given a set of SA2s that are known locations of confirmed cases of COVID-19, what are the other SA2s that share the greatest number of connections to the SA2s with confirmed cases?*

4.1 Method

A detailed description of the methodology used in the construction and analysis of the ACN is given in a previous report[3], which also includes further analysis of the underlying network to identify areas of high transmission risk and high age, health, and socio-economic vulnerability to COVID-19. Here we focus on applications of the ACN to the risk of COVID-19 spread in the early stages of the August 2021 outbreak. Section 5 uses further analysis of the ACN to suggest regional boundaries that might be used to mitigate that risk.

The source of data for the co-incidence network is obtained through the Aotearoa New Zealand Integrated Data Infrastructure (IDI). The IDI is a collection of government data sets, operated by Tatauranga Aotearoa Statistics New Zealand, containing micro-data from a range of sources linked at the level of individuals for the population of Aotearoa New Zealand. The ACN in built from data regarding individuals shared employment in workplaces and enrolment in schools. Given the various interaction contexts we include in the network, we draw upon several different data sources. We are able to derive information on nodes representing individuals and dwellings from the 2018 census. For workplace nodes with employee information, we use Inland Revenue tax records, while we obtain data on schools from school enrolment data. This includes information on primary school students up to high school. Both workplaces and schools data is obtained from the same time period as census 2018.

We begin by constructing a bipartite network consisting of dwelling nodes; and workplace and school nodes. We create edges between the dwelling nodes and the workplace and school nodes where individuals from that dwelling are employed or enrolled. We then simplify this network by "projecting" on to the dwelling nodes. In simple terms, this process involves drawing direct edges between dwellings that were originally connected via a pair of edges linking them to a shared workplace or school. The final step involves aggregating edges, between pairs of regions, at the level of the geographic regions (SA2s) in which dwellings are located.

The resulting network consists of regions (SA2s) connected to other regions by weighted links, where the link weight represents the total number of possible interactions between individuals living in the two regions. We have produced an associated web app[§] that allows for interactive exploration of the pattern of connections from any specified region or set of regions in Aotearoa. It is important to note that while the range of connections weights can appear large, the manner in which the network is structured explains how the weight of connection can increase quadratically if many individuals from a pair of SA2s share the same workplace or go to the same school. For example, if 100 students living in SA2$_i$ go to the same school as 100 students from SA2$_j$, the connection weight is 100×100 (i.e., each of the 100 students from SA2$_i$ connected to each of the 100 students from SA2$_j$), giving 10,000 potential interactions.

4.2 Results

We use the ACN to calculate and plot the number of connections (potential interactions) to SA2s from the set of SA2s that were the home to one of more confirmed cases of COVID-19, as at 21st August 2021. Figure 10 shows a heat map where the colour intensity indicates the number of connections for each SA2. This figure shows that **SA2s over a large geographic region; from Whangarei and Kaipara, to Coromandel and the Waikato have appreciable numbers of potential interaction connections, via work and school, with individuals from the SA2s with confirmed cases**. At a finer resolution, the heat maps also reveal that there is spatial heterogeneity in the number of connections to the SA2s with confirmed cases. That is, **some SA2s that are relatively spatially distant from the location of confirmed cases, nevertheless can have higher numbers of interaction connections.** SA2s with over 40,000 interaction connections are not uncommon.

5 Using the ACN to Determine Optimal Regional Boundaries

Given that we have calculated the number of potential work and school induced interactions between all possible pairs of regions in Aotearoa we are able to ask the further question *is there a way to find an optimal partitioning of those regions, such that more highly connected regions tend to be within the same set of regions as each other?* Such a partitioning would be a possible candidate for an optimal choice of a set of regional boundaries for containing any interaction mediated disease spread within the region.

5.1 Method

We apply the method of *modularity maximising community detection* to the weighted network that defines the ACN. Broadly speaking, modularity maximisation attempts to find a partitioning of a network into sets of nodes such that the strength of links between nodes *within each set* is greater than the strength of links between nodes (between sets). The number of sets that the nodes (or regions) are partitioned in to is not enforced. While there are a number of different modularity maximisation methods, we apply two of the more commonly used algorithms: the *Infomap* and the *Louvain* methods.

5.2 Results

The Infomap community detection algorithm detected 32 different communities on the ACN. In contrast the Louvain algorithm partitioned the same network into only 11 communities. The smaller number of larger communities found by the

[§] https://stur600.shinyapps.io/aotearoa-coincidence-network/

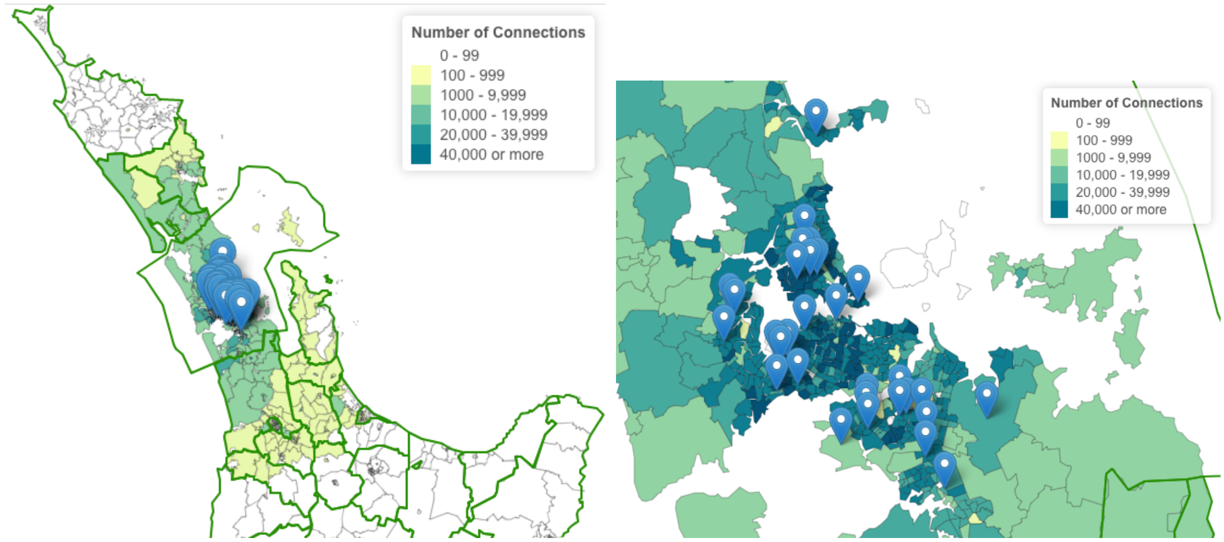

Figure 10. Heat maps showing the number of connections, via potential work and school interactions, from SA2s with one of more confirmed COVID-19 cases, as at August 21st, 2021. Boundaries of territorial authorities are indicated by the green lines. The zoomed in map on the right shows that regions can have large numbers of connections to a region with a confirmed case, even when they are relatively spatially distant.

Louvain method tended to be aggregations of the smaller Infomap communities. Given that both methods reached similar levels of modularity, both partitionings are comparable in terms of their ability to group highly connected regions together, and to distinguish such sets of regions from each other. There may be other — non-modularity based — reasons why one of the partitionings could be preferred over the other in the context of determining regional Alert Level boundaries.

The resulting communities are presented below in Figure 11 for both partitioning methods. We also present in Figure 12 the Infomap communities, compared with the boundaries of Territorial Authorities.

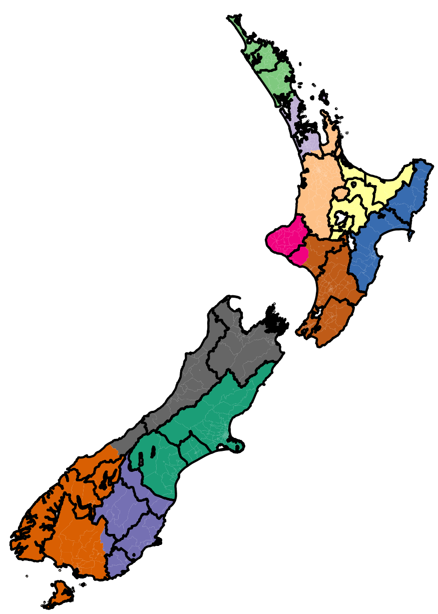

Figure 11. Louvain Communities Overlaid with Infomap Communities. The map presented above highlights geographic communities identified by the Louvain community detection algorithm (coloured), with the communities identified by the Infomap algorithm (black lines).

Figure 12. Aotearoa Co-incidence Network Communities. This map highlights geographic communities that are detected by the Infomap community detection algorithm when we consider the connections that individuals share through co-employment in the same workplaces, and co-enrolment in the same schools. Territorial Authority (TA) boundaries are superimposed with black lines. We find much in common with the overlap between TA boundaries and the boundaries of the detected communities, although the communities cover the area of multiple TAs. Importantly, this map highlights the fact that in reality TAs often share many connections.

Figure 12 highlights the geographic communities that are present when we consider the connections that individuals share through co-employment in the same workplaces, and co-enrolment in the same schools. Importantly, these communities strongly reflect established TA boundaries with a few exceptions. There are some instances where the boundaries of the communities do not line up with established TA boundaries. Firstly the Auckland community extends further south than the Auckland TA boundary, to SA2s such as *Port Waikato-Waikaretu* and *Maramarua*. Secondly, the TA of Ruapehu is split across the middle along the boundary of *National Park* and *Tangiwai*. Westland TA is also split along the border of SA2s *Waitaha* and *Westland Glaciers-Bruce Bay*. Finally, Ashburton TA is also split, such that Ashburton Lakes (an SA2 located between Mount Sunday, Mount Hutt, and Mount Barrosa) is included in the neighboring community that contains Christchurch, Selwyn and Hurunui. While there is no reason *per se* for the regions identified by our community detection method to match the bureaucratically defined boundaries of Territorial Authorities (TAs), the common definition of TAs as regions based on community interests and roading access is not entirely dissimilar to the concept of communities formed from areas where people are likely to interact through work or education.

The extended southern border of the community centered on Auckland, with respect to the Auckland TA is explained by the high level of commuting that occurs from regions south of Auckland. It is also worth noting that during August 2020 community outbreak of COVID-19 in Aotearoa New Zealand, when a regional level lockdown was first applied to Auckland TA, it was found that the regional intervention caused significant disruptions for workers commuting across the southern TA border. The position of this southern border was adjusted, to approximately the location of the southern Auckland border in the ACN communities during a second regional lockdown in February 2021[4].

The other two regions (Ruapehu and Westland) where there are notable distinctions between the ACN communities and the TA boundaries are likely to be explained by significant features of natural geography which reduce connectivity between these neighboring SA2s.

6 Discussion and Summary

The current report has provided a detailed summary of movement patterns across Aotearoa New Zealand through the various methods and exploration of several different sources of data. Given the context of the latest Auckland outbreak of COVID-19 from August, 2021, this report aims to provide insights into the movement patterns from the Auckland region in particular.

Through the use of electronic transaction data, we are able to derive movement patterns to and from Auckland at a ‘normal’ baseline level (using data from 2019), and compare this to the levels of movement observed during an Alert Level 4 scenario (using data from August 2020). We find that in Alert Level 4, the number of trips to and from Auckland dramatically declined, going from a baseline level of around $\sim$ 100,000-150,000 trips to under $\sim$50,000). Through use of this data, we also identify Hamilton, Christchurch, and Wellington as TAs with the greatest number of trip *into* Auckland in the week preceding the AL4 lock-down in August 2020. In this same time period, Queenstown Lakes, Wellington, and Hamilton were the destinations of the greatest number of from trips out of Auckland.

Without considering the available epidemiological data (i.e. ignoring the existence of known movements of confirmed cases of COVID-19 from Auckland to Wellington, but not to Christchurch), the **movement estimates above would suggest that Wellington and Christchurch are at equal risk of onward transmission of COVID-19 from Auckland**, due to similar numbers of movements to/from Auckland in the week before August 17th, 2021. **Hamilton/Waikato is at slightly higher risk**, especially when is is considered that in addition to the ‘long-range’ trips represented by the electronic transaction data, there are also large numbers of potential links identified in the Aotearoa Co-incidence Network, from Auckland to Hamilton/Waikato, which may not be represented in electronic transaction data. **The risk of onward transmission from Auckland to the Queenstown Lakes region is estimated to be slightly lower than that between Auckland and Wellington or Christchurch**. This is because although there are a larger number of trips from Auckland to Queenstown Lakes, theses trips are not reciprocated by residents of Queenstown Lakes travelling to Auckland.

In terms of traffic movements, various sources of data were explored. Traffic flow data from NZTA highlighted the strong impact that previous alert levels have had on the number of vehicles travelling through sites heading northbound or southbound from Auckland. Data available to-date for the effect of AL4 on traffic in and out of Auckland suggests that the intervention is as effective in previous periods of AL3 and AL4; though an increase of traffic counts leaving Auckland to the north, between the announcement of AL4 and it coming in to effect at 11:59pm is of concern for potential spread of COVID-19 into Northland.

Vehicle movement data inferred from Apple mobility records show a similar level of reduction (around 75-80%) for vehicle movements both nationally, and within the Auckland region. Significantly, the Apple mobility data also reveals the difference in mobility patterns within the Auckland region between periods at AL3 and AL4, with the reduction being around 40-50% great during AL4, compared to AL3. I.e. intra-region movements for Auckland are much reduced at AL4 (c.f. AL3) while inter-region movements for Auckland were equally reduced at both AL4 and AL3.

The current report also summarised potential transmission pathways from the current Auckland August 2021 outbreak through use of the Aotearoa Co-incidence Network (ACN). The ACN details the secondary connections that an SA2 has with other SA2s through inhabitants having shared workplaces or schools. We find that SA2s have a number of potential interaction connections across a wide geospatial areas, via work and school, with individuals from the SA2s with confirmed cases, with this ranging from Whangarei and Kaipara, to Coromandel and the Waikato. Since the majority of these interactions are prevented by an increase in alert levels, the ACN tells us about the risk of transmission in the period before 17th August 2021, and about the potential transmission risk if alert levels were to be reduced.

We also use the ACN to derive a set of geospatial boundaries that best partition regions according to the connections individuals share across workplace and school contexts. These partitionings have implications for setting any regional boundaries for different alert levels. Importantly, the resulting community boundaries from the ACN share many similarities with current TA boundaries (or aggregations of TAs), with some exceptions. In Auckland specifically for example, the ACN boundary is extended to SA2s slightly further north, and further south. The ACN boundary more accurately reflects the adjusted Auckland boundary established during the second regional lockdown in Auckland, February, 2021.

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