

Estimating the effect of selective border relaxation on COVID-19 in New Zealand

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ABSTRACT

AIMS: We developed a model, updated daily, to estimate undetected COVID-19 infections exiting quarantine following selectively opening New Zealand's borders to travellers from low-risk countries.

METHODS: The prevalence of infectious COVID-19 cases by country was multiplied by expected monthly passenger volumes to predict the rate of arrivals. The rate of undetected infections entering the border following screening and quarantine was estimated. Level 1, Level 2 and Level 3 countries were defined as those with an active COVID-19 prevalence of up to $1/10^5$, $10/10^5$ and $100/10^5$, respectively.

RESULTS: With 65,272 travellers per month, the number of undetected COVID-19 infections exiting quarantine is 1 every 45, 15 and 31 months for Level 1, Level 2 and Level 3 countries, respectively. The overall rate of undetected active COVID-19 infections exiting quarantine is expected to increase from the current 0.40 to 0.50 per month, or an increase of one extra infection every 10 months.

CONCLUSIONS: Loosening border restrictions results in a small increase in the rate of undetected COVID-19 infections exiting quarantine, which increases from the current baseline by one infection every 10 months. This information may be useful in guiding decision-making on selectively opening of borders in the COVID-19 era.

At the time of writing, the New Zealand government allows only citizens, residents and a small number of other exceptions to travel to New Zealand, and all these travellers must undergo a 14-day managed isolation and quarantine (MIQ) on arrival. This policy has had a significant impact on New Zealand, particularly the tourism industry, which, before the COVID-19 era, accounted for 5.8% of the nation's gross domestic product (GDP).¹ Further, labour shortages are likely to restrict productivity in a wide range of industries, including agriculture and horticulture, along with creating humanitarian issues from the effective lockout of many partners of recent migrants.²

New Zealand has had relatively few cases of COVID-19, with a total of 1,683 confirmed test-positive cases and 25 deaths at the time of writing. At present, 67% of all cases have been either imported or import-related.³ In an analysis of cases from February to May

2020, 6.3% required hospital treatment, and older age most strongly associated with either hospital treatment or death (crude odds ratio 26 comparing cases aged older than 80 years to those aged 20–34 years).⁴

Many countries are now enforcing border restrictions in proportion to the estimated risk of COVID-19 in the source country of the traveller.⁵ New Zealand, at present, is relatively restrictive compared to European and other English speaking countries, because New Zealand's border policy does not vary by the prevalence of infection at the country of departure, which is arguably the strongest determinant of border risk.

The risk of people exiting MIQ while infectious is largely related to the recent prevalence of infectious cases in the traveller's country of origin. Around the world, the prevalence of COVID-19 varies widely. Several locations (eg, Taiwan, Thailand) report no active, locally acquired cases. Some (eg, China, South Korea) report fewer

than 10 cases per 10^5 population. Others have high prevalence. For instance, the US, which now has over 900 active infections per 10^5 population. Testing and compliance with MIQ conditions can then further mitigate baseline risk.

At present, New Zealand relies on a 14-day MIQ system for all travellers, irrespective of the prevalence in their country of origin, to reduce the risk of imported infection. Because the risk of a traveller crossing the border with COVID-19 is related to the prevalence of infection in their country of origin, estimating risk by country could aid the planning of a risk-based border control system. Our aim was to estimate the rate COVID-19 would enter New Zealand following risk mitigation based on the traveller's country of origin.

Method

The risk of imported infection posed by international travellers can be estimated from the rate of infections in source countries, the volume of travellers coming from those countries and the success of border measures at reducing travellers' exit into the community while infectious.

Comprehensive details for all assumptions and formulae are provided in the appendices. Appendix 1 lists the supplementary online materials. All data presented here are based on prevalence data accessed on 22 August 2020. Daily updated data is displayed in a public, online dashboard, which will be maintained during the current pandemic: https://bnanalysis.shinyapps.io/border_covid_assessment/ (see Appendix 2 and Appendix 3). Appendix 4 provides details on the methods used to calculate country prevalence and transmission and mitigating steps during the traveller journeys. Inputs for the sensitivity analysis are provided in Appendix 5.

Prevalence

To estimate each country's up-to-date prevalence of infectious COVID-19 cases as accurately as possible, new cases, deaths and recovery data by country were obtained from John Hopkins' register (Appendix 4.1).⁶ Since asymptomatic COVID-19 infection is common, official case tallies may not accurately represent the true count of infections. To adjust for this, fatality counts were

assumed to be more accurately recorded. Fatality counts were divided by an infection-fatality ratio (IFR), 0.6%, which better describes a population-level IFR than a simple case-fatality ratio,⁷ and the resulting infection count estimate was compared to official case counts to estimate a country's detection rate. The detection rate then adjusts prevalence based on active case counts (Appendix 4.1.3). This upwardly adjusted prevalence is then assumed to apply to travellers from that country. In practice, IFRs differ according to a population's age structure and other factors, so we have examined implications of differing IFRs within a sensitivity analysis (see *Results, Sensitivity analysis*).

COVID-19 deaths may not be reliably assessed in source countries. To check the reliability of fatality counts, we used each country's life expectancy as a proxy, because it is a marker of a health system's capacity to detect cases (Appendix 4.1.4). Countries were then grouped into five risk tiers based on prevalence: COVID-19 free; Level 1 (>0 and <1 active COVID-19 cases/ 10^5 population); Level 2 (1 to $<10/10^5$); Level 3 (10 to $<100/10^5$); and Level 4 ($\geq 100/10^5$). These tiers had varying requirements for polymerase chain reaction (PCR) tests and duration of MIQ, with longer periods of MIQ for travellers from higher prevalence countries, since spacing out PCR tests improves the overall sensitivity of the two tests combined. Prevalence was multiplied by historic volumes of passenger arrivals to obtain a predicted rate per month of COVID-19 infections crossing New Zealand's border.

We considered source countries with more than 2,000 travellers to New Zealand in August 2019.⁸ We avoided a longer-run average in order to reflect the most recent travel patterns. In reality, any pre-COVID-19 travel data could only roughly approximate current expected travel patterns, but 2019 travel data provides a starting point for estimating travel under one demand scenario. The web app described here is designed to allow policymakers to estimate infection rates under any level of travel demand.

Journey risk

To account for an increase in risk based on observed rates of viral transmission on flights, a small multiplier of 0.43% was applied to the prevalence (Appendix 4.2.6).⁹

This multiplier will be sensitive to prevalence in source countries but not differing airline practices or flight lengths, and a sensitivity analysis (see *Results, Sensitivity analysis*) tests a higher level of spread (multiplier of 5%). The risk posed by an imported case may then be mitigated by screening and infection control on either side of the border, to either prevent travel or require MIQ after entering New Zealand for those who test positive (Figure 1). We calculated the risk mitigated using a pre-departure PCR test, MIQ of varying lengths on arrival and a second PCR test one day before the end of MIQ. PCR-positive cases detected in New Zealand were assumed to have their risk of infection mitigated almost completely by requiring 14 days in quarantine, following a previous modelling approach.¹⁰ Clinical studies were used to estimate the probabilities of symptoms, infectiousness and the PCR positivity of cases as a function of how many days before arrival each traveller was infected with COVID-19 (Figure 2 and Appendix 4.2.4).^{11–13} These were then combined across the traveller journey to estimate the aggregated sensitivity of border screening, considering both the risk of an infected traveller exiting MIQ undetected and the secondary risk (Appendix 4.2.7) of spreading the infection to another traveller in MIQ (Figure 3).

Designing traveller journeys

We designed three ‘traveller journeys’ based on the prevalence of infection in each country and risk reductions from screening and MIQ (Table 1). The three traveller journeys (below; Figure 3) apply to Levels 1, 2 and 3 and, in addition to separate treatments for COVID-free and very high-risk countries, are intended to limit undetected imported infections. For the purposes of our model, these were applied to all travellers, including New Zealand citizens, based on the country from which they were travelling.

Thailand, Taiwan, Western Samoa and the Cook Islands had no detected cases of infectious COVID-19 at the time of writing.¹⁴ Unrestricted travel from these countries and any others at the same Level could be allowed at minimal risk to New Zealanders. With regular surveillance, no imported infections are expected. Level 1, 2 and 3 traveller journeys include a pre-departure

PCR test, so that positive cases are prevented from boarding, to reduce the number of infections entering MIQ and thus to reduce spread. These journeys differ only in the length of MIQ applied and, consequently, the time from arrival to the final PCR test. Level 4 country calculations were carried out initially without pre-departure PCR (because only New Zealand citizens and exceptions are permitted at Level 4), but we provided some supplemental calculations describing an enhanced intervention with a pre-departure PCR included.

For Level 1, a 1-day MIQ and pre-flight PCR reduces risk by 70% (Table 1). For Level 2, a 5-day MIQ stay and pre-flight PCR reduces exposure to cases by 91% (Table 1). Observed data under current policy indicates that a 14-day MIQ effectively mitigates infection for between 98% and 99.9% of travellers.^{10,15} For Level 3, the 14-day MIQ is combined with the PCR pre-flight check, and our estimates indicate that 14-day MIQ screening reduces undetected infections by 99%.

A previous estimate¹⁰ of 5-day MIQ effectiveness with only one PCR test at day three was 75%, in comparison to our estimate of 91%. In contrast, our estimate (1) simulates some arriving cases becoming non-infectious in quarantine, (2) assumes a pre-departure PCR test and (3) expects a pre-release test at day four rather than day three. When simulating a more comparable 5-day MIQ with only one test at day three and no recoveries, our model estimates an effectiveness of 79%, down from 91%, which is only slightly higher than the previous estimate of 75%.

To simulate cases, the model assumes a volume of passengers from each country relative to both lockdown levels and pre-lockdown volumes. The baseline volume of passengers expected is the current number of travellers given heavily restricted borders. Relaxation of restrictions would lead to greater demand. For Level 1 and Level 2, 20% of the difference in volume between the baseline and August 2019 volumes was added. For Level 3, 5% of the difference was added; a 14-day quarantine is expected to deter most short-term visitors leaving only long-term travellers. These assumed volumes are only exploratory, and can be modified in the app.

From the prevalence and rate of expected travellers, along with the risk-based interventions applied, we estimated the rate of undetected infections from each source location.

Calibration

We compared model-predicted monthly rates of COVID-19 infection with observed rates at New Zealand’s border reported by the Ministry of Health. We used a constant multiplier to improve agreement between these measures. The multiplier was estimated by minimising the sum of squared residuals between observed and predicted monthly counts.

Analyses were conducted in R 4.0.2 and the web app developed in Shiny.

Results

Prevalence

For most countries, COVID-19 fatality rates indicated that active cases were likely to be under-reported. To compensate, we adjusted prevalence for countries across Levels 1–3 by a detection ratio (median: 1.7; IQR: [1.0, 3.3]; see Appendix 4.1.3). The estimated COVID-19 prevalence by country on 22 August 2020 is displayed in Table 2. Our estimated risk reduction for MIQs of varying lengths is similar to that reported previously.¹⁰

Aggregate journey risk per imported case

Relative traveller journey risk is illustrated in Figure 4 and further detailed in Appendix 6. The overall sensitivity of border screening measures for different spacings of PCR tests, with or without daily health checks, are outlined in Table 1 and are consistent with other published estimates.¹⁰

In the status quo MIQ, we assumed 11,271 people per month will enter, which was the number of travellers to New Zealand in August 2019 (Figure 1).¹⁷ At this volume of travel, we estimated 22 infectious cases per month would arrive at the border in August, of which 0.41 (one infection every 2.4 months) would exit MIQ while infectious.

With the introduction of our Level 1–3 measures, the rate of undetected COVID-19 infections exiting MIQ for Level 1–3 travellers based on modelled traveller journeys is shown in Table 2. Basing our models on an assumed fraction of August 2019 travel (Appendix 4.2.2), we estimated that 60,806 travellers a month would come from COVID-free and prevalence Levels 1–3 countries, in addition to 4,467 from other countries—up from 11,271 from all countries in August 2020.

Figure 1: Top line: Simplified COVID-19 border volumes per month released into New Zealand community given status quo policy. Bottom line: An example considering status quo risk as of 22 August 2020 as described in the results section. See Appendix 4.2 for more details.

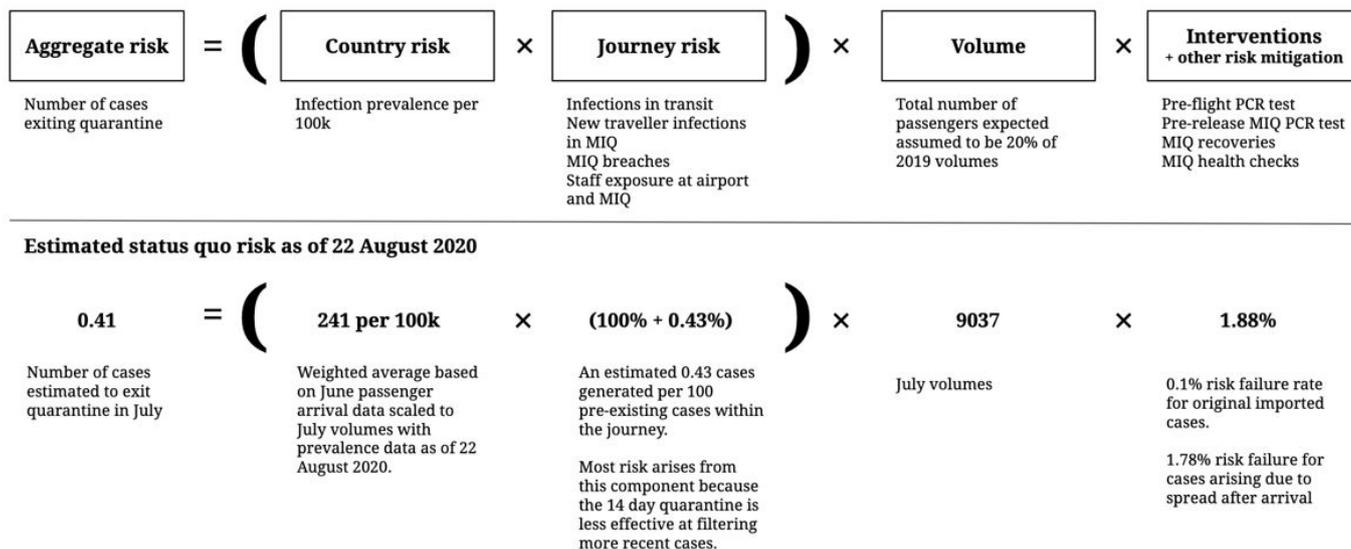


Figure 2: Test sensitivity, proportion of cases with symptoms and proportion of cases that are infectious by number of days since infection.^{11,12,16} See Appendix 4.2.4 for full details on curve design.

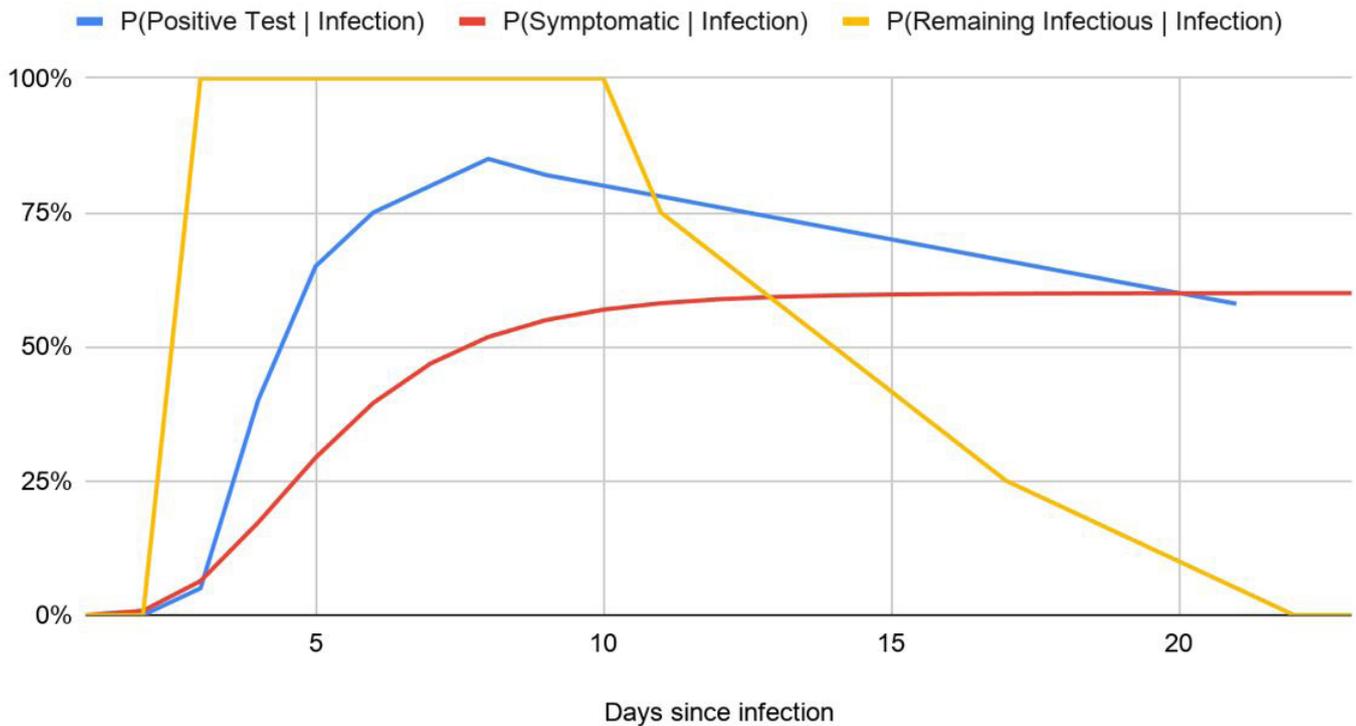


Figure 3: Risk considered at each stage of the traveller journeys. Journeys for Levels 1, 2 and 3 included four stages: pre-departure PCR, flight, managed isolation and quarantine and release. Traveller journey for COVID-free countries contains no risk mitigation measures. Traveller journey for Level 4 countries remains the same as status quo (ie, no pre-departure PCR and 14-day quarantine). See Appendix 4.2.7 for detailed information.

Event	PCR test 2-3 days pre-departure Proposed for Level 1, Level 2, Level 3 traveller journeys. Not included for travellers from Covid-free countries. Travellers must test negative to enter.	Flight	Managed Isolation/Quarantine Includes PCR test and assumes daily health checks. COVID-free: Not included. Level 1: 1 night, PCR on arrival Level 2: 5 nights, PCR on day 4 Level 3: 14 nights, PCR on day 3 and 12 Level 4: 14 nights, PCR on day 3 and 12	Release
Risk	Travellers enter the journey with a probability of having a Covid-19 infection equal to 120% of their country's population prevalence. Probability of infection is modelled equally over the 14 day period.	0.43% Risk of spread to air crew and other passengers who will subsequently enter MIQ.	0.63% MIQ breach risk over 14 days (July data; see Appendix 4.2.7). 1.1% Risk from 35 close contacts over 14 days ¹⁰ Risk for shorter MIQ periods is calculated proportional to the length of those MIQ periods.	Chance of primary traveller exiting quarantine undetected Level 1 29.9% Level 2 8.2% Level 3 14-day MIQ ¹⁰ 0.1% Level 4 14-day MIQ ¹⁰ 0.1%
Level 1	Pre-flight test		Test on arrival	1 day MIQ
Level 2	Pre-flight test		Test on Day 4	5 day MIQ
Level 3	Pre-flight test		Test on Days 3, 12	14 day MIQ

Given these expected travellers across all Levels, we estimate that 24 infections per month will enter the traveller journey; around half of those will be screened out in the pre-departure PCR test, and following MIQ, 0.50 (one infection every two months) will exit MIQ undetected. This represents an increase of 0.10 infections per month for the intervention, or one additional infection exiting MIQ every 10 months. This is equivalent to an additional 0.16 per 10⁵ (0.10 cases per month in 65,272 travellers) during the period measured, relative to current traveller risk of 3.6 per 10⁵ (0.40 cases per month in 11,271 travellers). The rate of infection arising from the source countries of each level is shown in Table 2.

If these changes were combined with a pre-departure PCR for all travellers, including New Zealand citizens and other travellers from high prevalence countries, the predicted risk would fall below the estimated status quo, to 0.35 infections/month, which means 0.05 fewer infections per month than the status quo.

Change in rate of undetected infections

This reduction is achieved by allowing travellers from COVID-free countries to enter New Zealand without screening (0 infections), travellers from Level 1 countries to enter with a 1-night MIQ (0.022 infections a month, 45 months per case), travellers from Level 2 countries to enter with a 5-night MIQ (0.069 infections, 15 months) and travellers from Level 3 countries to enter with a 14-night MIQ (0.032 infections, 31 months).

The analysis was extended by modelling the application of the Level 3 traveller journey to all people, including New Zealand citizen returnees, so that they would require a negative PCR test 2–3 days pre-flight to enable travel. Although we expect 24 cases entering the traveller journey when this policy is applied, some cases are screened out before their flight; these are not present in quarantine to pose a risk to others, and, consequently, we estimate only 0.35 infections per month (one every 2.9 months) will

Table 1: Estimated proportion of COVID-19 infections identified, with PCR and with or without health checks during MIQ.

Days from			Overall traveller journey aggregate sensitivity to detect COVID-19 cases		
Test 1 to Test 2	arrival to Test 2	arrival to release	without health checks	with health checks	with health checks including spread risk
2	0	1	68.6%	70.1%	69.8%
3	1	2	74.4%	76.2%	75.8%
4	2	3	80.5%	82.6%	82.2%
5	3	4	86.2%	88.5%	88.0%
6	4	5	89.6%	91.8%	91.3%
7	5	6	91.2%	93.4%	92.9%
8	6	7	92.9%	94.4%	93.9%
9	7	8	92.9%	95.0%	94.4%
10	8	9	93.3%	95.4%	94.8%

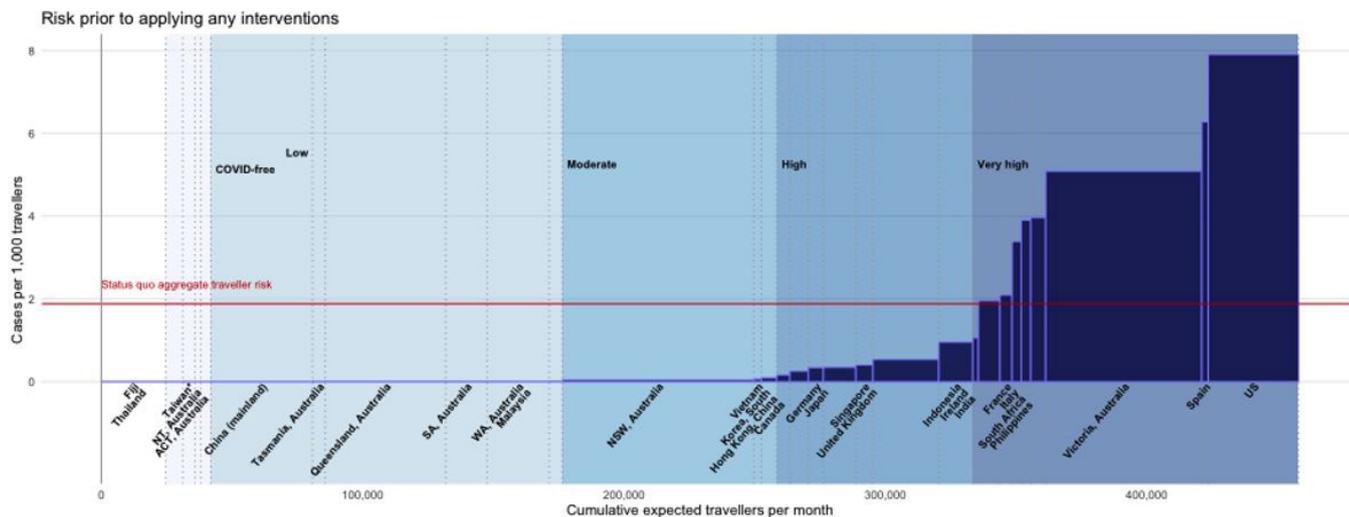
‘Spread risk’ includes the risk of COVID-19 spreading to other passengers during the flight and MIQ. Steyn, Binny, Hendy et al assumed a daily health check with 33% sensitivity per day for symptomatic cases. To simplify the model, we assumed just a single health check, on the same days as the PCR test, but assumed sensitivity of two consecutive health checks at an aggregate of 55%. Appendix 1 contains a link to the risk calculation spreadsheet used to calculate these values. Further details are in Appendix 4. MIQ, managed isolation and quarantine. PCR, polymerase chain reaction.

Table 2: Aggregate risk for selected countries by risk categories at 22 August 2020. Additional countries displayed at https://bnanalysis.shinyapps.io/border_covid_assessment/ and in the appendix.

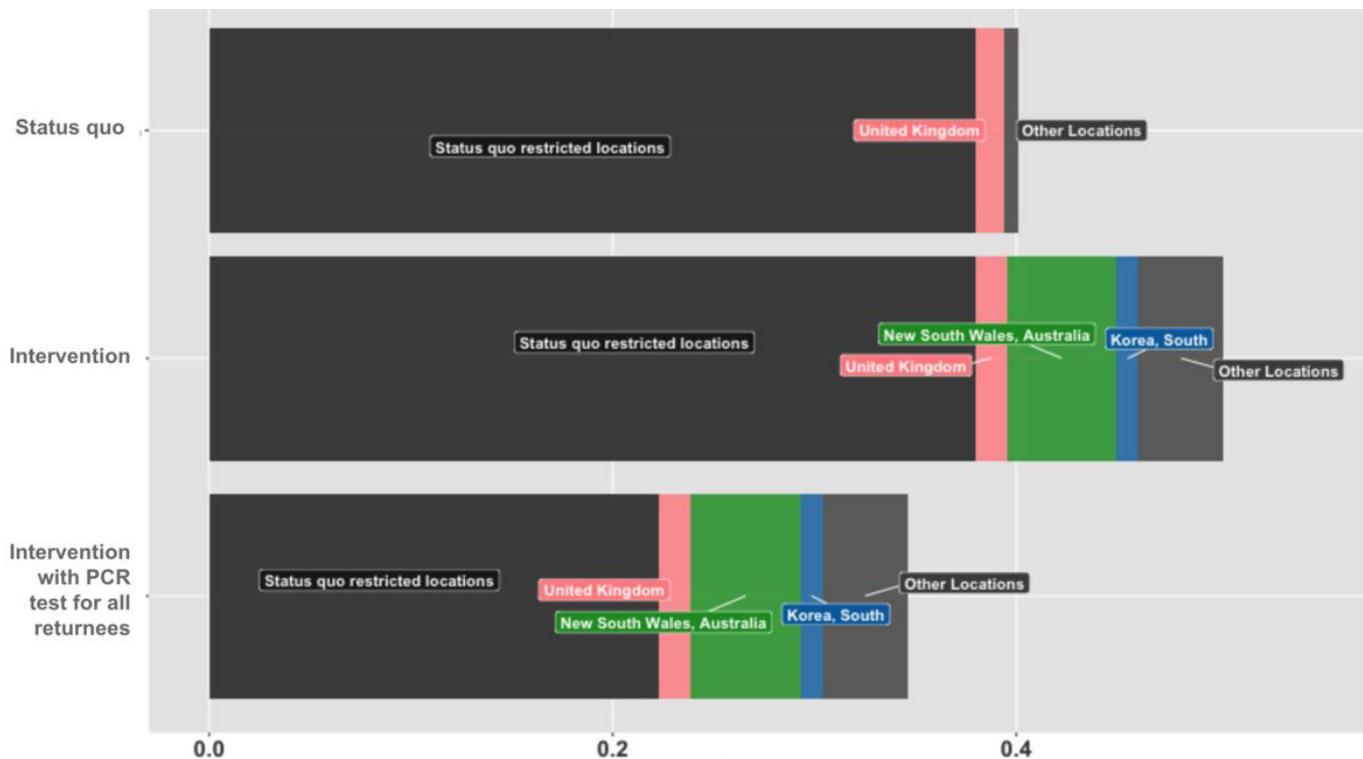
Countries	Level	Infection prevalence per 100k	Infections per 100k without border protocols	MIQ		Infections per 100k after border protocol	Monthly volume of travellers		Undetected infections per month (months to an infection)
				Nights	Effectiveness		% of 2019 levels	Count	
Cook Islands, Samoa, Taiwan, Thailand. Australia: ACT, NT	COVID- free	0	0.000	-	-	0.000	20%	8,218	0.000
China, Malaysia. Australia: TAS, QL, SA, WA	1	0–1	0.043	1	69.8%	0.013	20%	29,030	0.022 (45)
South Korea, Vietnam. Australia: NSW	2	1–10	6.529	5	91.3%	0.567	20%	17,647	0.0689 (15)
Hong Kong, Canada, Germany, Japan, Singapore, United Kingdom, Indonesia, Ireland	3	10–100	33.098	14	98.9%	0.368	5%	5,911	0.0319 (31)
							August 2020	Count	Current volume (months to an infection)
France, Italy, Spain, US. Australia: VIC	4	>100	227	14	98.2%	4.062	100%	2,560	0.298 (3)
India, Fiji, Philippines, South Africa	Unrated	104	14	98.2%	1.861	100%	832	0.0395 (25)	
All others	Various	1386	14	98.2%	24.785	100%	1,074	0.0423 (24)	

Sums of traveller numbers here do not include continued arrivals under the status quo system from countries excluded from our COVID-free and Level 1–3. Within each row, infections/100k are aggregated according to each country's population, not their New Zealand travel rates. The last row, *All others*, are all countries in the dataset outside of our 22-country shortlist. MIQ effectiveness described in more detail in Table 1. Undetected COVID cases/month across Level 1–3 sums to 0.123, made up of 0.012 risk from Level 1–3 countries in the status quo, plus 0.111 additional risk in the intervention. Infections per 100k for each level weigh each country by its population, so these figures cannot be used directly to find the undetected infections/month in the last column, which is weighted relative to the volume of travellers from each country to New Zealand. For instance, the infections per 100k values for Level 1 mainly reflect China, since China's population makes up the vast bulk of the population within Level 1 locations. However, undetected infections per month give much more weight to Australian states listed because of the larger volume of travel from Australia relative to China.

Figure 4A: Baseline traveller risk of imported COVID-19 before applying interventions. The width of each bar represents the number of travellers from each country in August 2019, and the height represents counts of infectious cases expected per 1,000 travellers. The area of each bar is proportional to the number of cases that would be expected under 2019 conditions if travel were opened without restriction.



Figures 4B: Expected cases exiting quarantine into the community across countries in three scenarios: the status quo, the risk-based travel interventions and the intervention combined with a PCR test for all returnees.



exit MIQ undetected, which is 0.05 (13%) lower than the status quo rate of 0.40 per month.

Model validation and adjustment

We compared our predicted rates of border-detected COVID-19 infections with observed infections to assess the validity of our model (Table 3). Only values from 'trusted' locations were compared, because predictions about other locations may not be reliable. We measured the monthly predicted infections imported from trusted locations based on prevalence rates estimated for the 15th of each month. We then collated data from daily Ministry of Health press releases to tally the observed number of cases imported from trusted locations. Then, we compared the observed and predicted numbers of cases. We estimated a constant prediction multiplier that minimised the sum of squared differences for all four months: 0.78. Because this would lower the total number of predicted cases, we conservatively opted not to include this in our final predictions presented here.

Sensitivity analysis

Sensitivity to variations in predicted undetected infections exiting MIQ were tested by changing parameter point estimates (Table 4). Using our chosen point estimates, the rate of infections exiting MIQ increased by 0.10 each month (one additional infection every ten months). In comparison, the highest additional risk obtained through changing any one point estimate came when assuming 20% lower PCR sensitivity and two days' additional incubation period (see Appendix 5, Figure

5.1); under this scenario, the intervention increased undetected infection rates by 0.22 infections per month (one every five months). Raising traveller volumes to very high levels increased undetected infections rates by 0.21 per month (one every five months). The next most sensitive parameter was prevalence of COVID-19 in travellers. If this were doubled, the rate of additional undetected infections per month increased by 0.16 per month (one more every six months). If MIQ breach risk was increased to one out of every 34 COVID-positive travellers, infection rates increased by only 0.12 per month (one every eight months). Flight transmission risk also made little difference—if this was 5% rather than the 0.43% used in this paper, infections would only increase by 0.13 per month (one every eight months). Constraining the traveller volume to 10% and 5% respectively for Level 2 and Level 3 while Level 1's traveller volume remained at 20% decreased undetected infections to 0.07 per month (one expected every thirteen months).

Discussion

We estimated the rate of undetected COVID-19 infections exiting MIQ, basing our estimate on country prevalence and intervention measures and selective relaxation of current border policies. With the introduction of the proposed measures, the overall rate of undetected active COVID-19 infections exiting MIQ is expected to increase from 0.40 to 0.50 per month, an increase of one every 2.5 months to 2 months, or from 4.8 to 6.0 cases per year.

Table 3: Observed vs predicted cases arriving in New Zealand from trusted locations.

Month	Total number of travellers	Trusted location: Predicted cases	Trusted location: Observed cases	Predicted–Observed	Adjusted prediction
July	9,037	24	13	11	19
August	11,271	29	8	21	22
September	11,482	16	19	-3	13
October	12,096	57	52	5	44
Total	43,886	126	92	34	98

'Trusted locations' are those where health systems are considered robust due to a life expectancy of 70 or greater. Predictions for each month were drawn from a simulation based on prevalence values drawn from the 15th day of each month.

Table 4: Sensitivity analysis, showing the influence of various parameters on the monthly rate of undetected COVID-19 cases exiting managed isolation and quarantine.

Parameter to test	Default value	Test value	Status quo cases in community per month	Intervention cases in community per month	Intervention as absolute increase per month
(Standard)*			0.40	0.50	0.10
IFR; traveller prevalence	0.6%; 100%	0.2%; 65%	0.66	0.77	0.11
		1%; 100%	0.24	0.32	0.08
Traveller prevalence	100%	200%	0.80	0.96	0.16
Traveller volume (Level 0; Level 1; Level 2; Level 3)	20%; 20%, 20%; 5%	20%; 20%; 10%; 5%	0.40	0.47	0.07
		50%; 50%; 25%; 20%	0.40	0.61	0.21
Quarantine breach risk	1/150	12/9000	0.29	0.40	0.11
		1/34	0.89	1.01	0.12
Quarantine contacts	35	1	0.17	0.27	0.10
		70	0.63	0.74	0.11
Quarantine health checks efficacy	55%	0%	0.40	0.52	0.12
Symptomaticity	60%	90%	0.40	0.49	0.09
		30%	0.40	0.51	0.11
Flight transmission	0.43%	0.09%	0.39	0.49	0.10
		5%	0.54	0.67	0.13
PCR test sensitivity	20% lower and delayed by 2 days	0.40	0.62	0.22	
Infectious period is two days longer	(see Appendix 5, Figure 5.1)	0.40	0.51	0.11	

*In the standard model, infection fatality rate (IFR)=0.6%, traveller prevalence=100%, traveller volume=20% for Level 0–2 and 5% for Level 3, quarantine breach risk=1/150, quarantine contacts=35, quarantine health check sensitivity=55%, taken on the same day as the PCR test, asymptomaticity=40% and infectious period is as modelled in the main paper, based on van Kampen et al (2020). For quarantine breach risk, 1/34 is the number of COVID-positive MIQ detainees reported breaching their conditions in July out of all COVID-positive July detainees; 12/9,000 is the total amount of the same, irrespective of COVID-positive status, and 1/150 is the log-average of the two fractions. Traveller volume was tested with varying rates from the COVID-free level to Level 3; Level 4 is assumed to stay constant as this proposal does not affect Level 4 travel.

Our plan allows an additional 53,372 travellers from low-risk countries, as of August 2020, a risk similar to that from 16,757 travellers under the existing system from the UK or just 707 additional travellers from the US. If all returnees, including New Zealand citizens, who return from Level 4 countries complete a PCR test before departure, we estimate only 0.35 infections per month (one every 2.9 months) would exit MIQ undetected, which is 0.05 lower than the status quo of 0.40 per month.

Limitations of our study

We have tried to balance simplicity with complex reality by focusing attention on factors that are most important and that most reduce uncertainty in our outcome measure—that is, the risk of release of undetected infection after selective border relaxation. Our sensitivity analysis demonstrates that sensible variations in many values, such as MIQ transmission risk, health check efficacy and typical infectious period, make little difference to the risk posed by selective border relaxation. Some of our model parameters, such as the sensitivity of repeated PCR tests, have inherent assumptions. We have assessed the validity of our model by comparing its predictions to historical data, but access to more detailed incoming infection rate data, ongoing monitoring of model assumptions and real-time alignment of predictions with the observed rates would be essential, should the model be used in practice.

Prevalence calculation strengths and limitations

We accounted for infection under-reporting but assumed fatalities are accurate and that infection-fatality ratios are constant between countries. Considering comparisons of excess deaths with COVID-19 fatality reports for US states¹⁹ and countries around the world,²⁰ fatality count is likely to be an accurate measure of deaths due to COVID-19. The adjusted infection count is based on an assumedly constant infection-fatality ratio that may vary between populations, particularly between those with different age structures. In our method we also assumed that the average time from test result to death is 21 days.^{7,21} We assumed specific travel numbers, and, as our sensitivity analysis demonstrates, different traveller

numbers will proportionately alter the risk of undetected infection crossing the border into New Zealand.

Data reliability will need to be closely considered for some countries. Some may suppress reporting of outbreaks. Should this policy be enacted, we encourage New Zealand authorities to verify data directly from overseas health authorities.

Our analysis does not distinguish between brief (eg, a 90-minute MIQ breach) and prolonged community exposures (eg, an undetected infectious case exiting MIQ); it simply attempts to estimate the count of cases exposed to the community.²¹ The risk arising from undetected infections exiting MIQ have been estimated by other authors.¹⁸

Traveller journey intervention strengths and limitations

As well as PCR screening, we considered other interventions, such as temperature and symptom screening. Studies show that temperature screening is not an efficient method of detecting infections during travel.²² Moreover, because 10–70% of infections are asymptomatic, it is unlikely to detect many cases.^{13,23,24} Nevertheless, we accept these checks could be helpful during MIQ and have included them within our risk calculations (Table 1).

We believe our MIQ breach risk estimate is conservative because the psychological pressure of a shorter confinement is likely to be lower, and thus cooperation is likely to be higher for periods shorter than 14 days. We have not calculated the probability of a community outbreak given the rate of exposure to infections. Accurately estimating this risk is critically dependent on understanding levels of immunity in New Zealand, for which there is now very little information. Other work could be extended using the same methods to estimate risk of community transmission.¹⁸ As New Zealand's existing contact tracing facilities become more developed, the risk that a single case extends to community outbreak will likely reduce.

Novelty and operational context

While there is one pre-print publication assessing the risk of opening New Zealand's border to Australia, no other reports assess a wider border-reopening risk,¹⁸ this report

examines travel from our highest source countries. The online dashboard displays up-to-date risk for over 100 countries.

Other countries have applied a variety of border policies. Travellers to Iceland, for example, must fill in a pre-registration form and are encouraged to download a COVID-19 tracing app to use during their stay. Iceland requires two PCR tests and five days of quarantine after entering the country.^{25,26}

Taiwan maintains successful elimination of COVID-19. The island nation allows travel for purposes other than tourism and social visits and requires a COVID-19 test taken three days or fewer before entry to the country, in addition to a 14-day MIQ.²⁷ Thailand, another nation with elimination status, essentially prohibits all entry by foreign nationals, with rare exceptions.²⁸

Managing risk: outstanding operational concerns

This paper may be the first to estimate COVID-19 prevalence in all countries and to provide a means of dynamically tracking border risk of imported infection. Country risk level has the potential to change over time. However, as countries move up or down levels, different screening and quarantine policies aim to keep per-traveller risk within a theoretical range from 0 to 0.9 infections per 10^5 , but typically towards the low end of that range, at just 0.19 per 10^5 during the period measured, relative to the current traveller risk of 3.6 per 10^5 . The online dashboard provides daily updated prevalence.

For countries with infection prevalence too high for Level 3—even though no relaxation of current controls have been proposed with a low volume of travellers—the estimated risk of imported infections exiting MIQ is high: currently, this risk is 5.3 per 10^5 or one every four months at current rates. Therefore, even slightly more stringent controls on this group are likely to substantially reduce rates of infections across the border. Specifically, universal pre-departure PCR, combined with the other interventions proposed here, would reduce risk by 15% from the status quo while allowing over 55,000 more people a month to travel to New Zealand.

If this approach were to be enacted, there are many operational questions beyond the scope of this paper that would need answering. The quality, accessibility and reporting times of COVID-19 tests performed outside New Zealand would need to be assessed. The New Zealand MIQ system would have to be expanded. Although the total number of rooms across all New Zealand hotels and motels is around 63,000, the existing MIQ system has effective capacity for only 7,316.^{8,29} Tracking travellers and enabling contact with them during their stay would be highly desirable (eg, Bluetooth technology could facilitate more efficient contact tracing and further mitigate the risk of COVID-19 outbreak beyond the border).

Application of the proposed risk-based 1- and 5-night MIQ for pre-screened travellers from lower-risk countries could considerably increase the rate of travellers the MIQ system is able to process. Travellers from Level 2 countries could be processed more than twice as fast as in the current system, and travellers from Level 1 countries could be processed seven times as fast as travellers under the status quo. While changes like these would mainly benefit tourism, many other sections of society may benefit as well, such as workers for agriculture, horticulture and aged and residential care. Risk-based pathways would also benefit education providers. This benefit is countered by the marginal increase in risk of undetected infection.

Conclusion

Overall, we estimate the magnitude of ongoing risk of COVID-19 entering New Zealand under the status quo border policy. There is a small marginal risk of selectively opening New Zealand's border with risk-adjusted traveller protocols. A number of logistic arrangements to support this policy, and greater verification of up-to-date prevalence of COVID-19, would be necessary. A careful comparison of the model's sensitivity to variations of its assumptions, and a comparison of predictions with observed data, as they become available, with suitable adjustments to the model in response to discrepancies, would be essential for successful implementation of this model.

Addendum, 27 January 2021

Since this paper was written, the New Zealand Government has adopted policy consistent with our proposal to introduce universal pre-departure PCR testing. In terms of relaxation of border policy, the Cook Islands and Australia have been engaged to allow quarantine-free travel, which at present is only partially implemented and is fragile in the event of new outbreaks. Our belief is that the additional risk from relaxation of border policy discussed here is effectively mitigated by the introduction of universal pre-departure PCR testing.

The estimated prevalence of COVID-19 across incoming passengers, weighted by 2019 passenger volumes, has increased from 2 to 12 per 1,000, which is around a six-fold increase. Correspondingly, most locations have moved up one risk Level since the time of writing: several formerly COVID-free countries are generally now Level 1; some formerly Level 1 countries now have Level 2 prevalence. This is not entirely unexpected, as we observed fluctuations in prevalence while preparing this article. Prevalence in some countries has moved in the opposite direction. Vietnam, for example, now has substantially lower prevalence and has thus moved from Level 2 to Level 1 in our model. We emphasise that the orders of magnitude in source country prevalence, and consequently the effectiveness of implementing a risk-based system to manage risk, has not changed. The changes in prevalence from the time of writing to publication underscores the importance of updating risk assessment when implementing such a border policy. The model is expected to respond to changing epidemiological circumstances (eg, transmissibility of strains and impact of vaccines through changing country prevalence).

Appendix

Appendix Figure 1: Table of contents of *Appendix to Estimating the effect of selective border relaxation on COVID-19 in New Zealand*. Read the complete appendix online: <https://uploads-ssl.webflow.com/5e332a62c703f6340a2faf44/601a08af102ff565f674add4886%20-%20appendix.pdf>

Appendix to ‘Estimating the effect of selective border relaxation on Covid-19 in New Zealand’

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Competing interests:

Benjamin J Smith, Arthur J Morris, Stephen Child and Simon Thornley were contracted by Auckland International Airports Limited to conduct this research. Ben Johnston is employed by Air New Zealand Ltd.

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