TE TAI ŌHANGA
THE TREASURY

Reference: 20210519

21 February 2022

T Baker
fyi-request-16178-9ff2b0bb@requests.fyi.org.nz

Dear T Baker

Thank you for your Official Information Act request (OIA), received on 3 November 2021. You requested the following:

> *-information related to the Modelling Governance Group established by the Ministry of Health:*
> *- Members of Modelling Governance Group.*
> *- Modelling Governance Group terms of reference.*
> *- Fee structure and cost incurred to date by Ministry by all activities associated with the Modelling Governance Group.*
> *- Conflicts of interest declared by members of Modelling Governance Group.*
> *- All modelling reports provided to Modelling Governance Group.*
> *- All minutes of meetings of Modelling Governance Group.*
> *- All comments made to reports issued to Modelling Governance Group.*
> *- All emails received or issued by the Ministry, by the Government, and by members of the Modelling Governance Group, associated with the Modelling Governance Group since group was appointed.*

The time to respond was extended by 35 working days. Your request was transferred to The Treasury as the agency responsible for convening the COVID-19 Modelling Governance Group.

The Terms of Reference for the group lists the officials who are members of the group. There is no fee structure or cost incurred directly by the group (as it does not include external participants), and no conflicts of interest have been declared by the members. Agendas and associated reports considered by the group will be attached, as well as relevant correspondence held by The Treasury. Formal minutes of the group's meetings are not kept, although the correspondence does include some discussion of the content of meetings.

Information being released

Please find enclosed the following documents. These documents are mainly made up of emails that the Treasury holds and are within the scope of your request.

1 The Terrace
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New Zealand
tel. +64-4-472-2733

https://treasury.govt.nz

Item	Date	Document Description	Decision
1.	February 2021	COVID-19 Modelling Governance Group- Terms of Reference	Release in full
2.	14 July 2021	Email: key points and actions from the Modelling Group	Release in part
3.	14 May 2021	Email: Agenda and papers for Modelling Governance Group	Release in part
4.	29 June 2021	Email: Publication of TPM vaccination modelling	Release in part
5.	5 May 2021	Email: Draft proposed for COVID-19 Modelling Governance Group	Release in part
6.	14 April 2021	Email: Draft Agenda for 14 April COVID-19 Modelling Governance Group	Release in part
7.	13 April 2021	Email: Draft Agenda for 12 April COVID-19 Modelling Governance Group	Release in part
8.	13 April 2021	Email: Draft Agenda for 12 April COVID-19 Modelling Governance Group	Release in part
9.	13 April 2021	Email: Draft Agenda for 12 April COVID-19 Modelling Governance Group	Release in part
10.	23 February 2021	Email: COVID-19 Modelling Group	Release in part
11.	17 February 2021	Email: Proposed agenda for modelling steering group	Release in part
12.	15 February 2021	Email: Vaccination and testing of the border workforce	Release in part
13.	15 December 2020	Email: overview of what the modelling governance role looks like	Release in part
14.	1 September 2021	Email: Agenda and papers for Friday's COVID-19 Modelling Governance Group	Release in part
15.	8 November 2021	Email: Upcoming TPM paper release	Release in part
16.	1 September 2021	Email: Agenda and papers for Friday's COVID-19 Modelling Governance Group	Release in part
17.	28 October 2021	Email: Agenda and papers for Friday's COVID-19 Modelling Governance Group	Release in part
18.	16 September 2021	Email: COVID strategy modelling catch up	Release in part
19.	31 August 2021	Email: COVID-19 Modelling Governance Group	Release in part
20.	11 August 2021	Email: Confidence under embargo COVID-19 vaccines strategies for Aotearoa	Release in part
21.	14 July 2021	Email: Confirmed agenda and papers	Release in part
22.	9 July 2021	Email: Confirmed agenda and papers	Release in part
23.	11 May 2021	Email: Agenda and papers for Friday's COVID-19 Modelling Governance Group	Release in part

I have decided to release the relevant parts of the documents listed above, subject to information being withheld under one or more of the following sections of the OIA, as applicable:

- names and contact details of officials, under section 9(2)(g)(ii) – to maintain the effective conduct of public affairs through protecting Ministers, members of government organisations, officers and employees from improper pressure or harassment, and

- direct dial phone numbers of officials, under section 9(2)(k) – to prevent the disclosure of information for improper gain or improper advantage.

Direct dial phone numbers of officials have been redacted under section 9(2)(k) in order to reduce the possibility of staff being exposed to phishing and other scams. This is because information released under the OIA may end up in the public domain, for example, on websites including Treasury's website.

Information publicly available

The following information is also covered by your request and is publicly available on the websites below:

Item	Date	Document Description	Website Address
1.	29 September 2021	Vaccination and testing of the border workforce for COVID-19 and risk of community outbreaks: a modelling study	https://royalsocietypublishing.org/doi/full/10.1098/rsos.210686
2.	March 2021	Effect of vaccination, border testing, and quarantine requirements on the risk of COVID-19 in NZ: A modelling study	https://www.sciencedirect.com/science/article/pii/S2468042721000877

Accordingly, I have refused your request for the documents listed in the above table under section 18(d) of the OIA:

- the information requested is or will soon be publicly available.

In making my decision, I have considered the public interest considerations in section 9(1) of the OIA.

The included papers *Frequency of Serious Outbreaks in COVID-19 in a Partially Immune Population* and *Visualising the effect of restrictions on travellers* were shared as a "work in progress" for feedback rather than as final advice and are incorporated into item 2 above.

Please note that this letter (with your personal details removed) and enclosed documents may be published on the Treasury website.

This reply addresses the information you requested. You have the right to ask the Ombudsman to investigate and review my decision.

Yours sincerely

John Beaglehole
Manager, Economic Policy

Table of Contents

February 2021

COVID-19 Modelling Governance Group

Terms of Reference

1. Purpose

1.1 The COVID-19 Modelling Governance Group (CMGG) has been established to support the Government's COVID-19 elimination strategy.

1.2 The CMGG will govern the provision of timely and policy-relevant model-based evidence to inform proactive decision making and responses to manage COVID-19 and its impacts.

2. Role of the Group

2.1 The Group will:

a. Provide strategic direction and oversight of the modelling programme to ensure it contributes effectively to the COVID-19 response and so the COVID-19 Modelling Steering Group can prioritise within that framework.

b. Prioritise the epidemiological, economic and social questions to be answered through modelling work

c. Remove barriers to manage resource needs funding, data, capability in respective agency

d. Facilitate dissemination, socialisation and champion modelling outputs

3. Membership

3.1 The Group will be chaired by Bryan Chapple (the Treasury) and membership of the group will be Stats NZ (Vince Galvin), Juliet Gerrard (Prime Minister's Chief Science Advisor), MBIE (Paul Stocks), DPMC COVID-19 Group (Cheryl Barnes), MSD (Nick Blakeley), MOH (Ian Town).

3.2 Membership may be adjusted as required to accommodate changes in scope or focus.

4. Meetings

4.1 The Group will initially meet not less than quarterly unless the group agrees otherwise.

From:	Christopher Nees [TSY]
To:	Alice Hume [DPMC]; ^EXT: Talosaga Talosaga; Bryan Chapple [TSY]; xxxxx@xxxxxxxx.xx.xx ; Juliet Gerrard [DPMC]; xxxxx.xxxxx@xxxxx.xxxx.xx; ^EDU: Paul Stocks
Cc:	Patricia Priest; Patricia Priest; George Whitworth [DPMC]; Pubudu Senanayake; Ryan Walsh [TSY]; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; xxxx.xxxx@xxxxxx.xxxx; xxxx.xxxxxxxx@xxx.xxxx.xx; Samantha Fitch; Hamish Spencer
Subject:	Key points and actions from the Modelling Governance Group
Date:	Wednesday, 14 July 2021 10:22:00 AM
Attachments:	Modelling oversight.pptx image002.png

Kia ora koutou

Thank you for your time at the Governance Group meeting yesterday. Here's a brief record of the key points and actions – please let me know if it needs any amendments. One thing I didn't clarify was who would initially approach Shaun to inform him of the new arrangements. Alice I think that sits with DPMC but happy to be corrected?

1. Context sharing

   - Tony Blakely will be visiting NZ shortly and has made a general offer to meet with officials. **Action: Ian** will invite the Steering Group members to a workshop with Tony.

   - Juliet noted interest in understanding what an achievable level of vaccination combined with other public health measures would look like as we

   - MBIE has found further $2m funding for TPM to cover their work post-August. DPMC will takeover lead of the contract from MBIE. **Action: DPMC** to communicate the plan to TPM

   - Treasury offered to continue to play the same role we are currently planning in chairing the groups.

2. Large outbreaks paper

   - The group endorsed the proposed next steps for further modelling, noting the need for it to be timely (end July) to fit with the RNZ policy programme, and to address the questions from Sir Skegg's group. **Action: George** to circulate the questions from Sir David's group to the Steering group

   - The Group also noted the need to be clear about what the modelling results tell us – i.e. they can guide us about what are the most important factors in reducing risk, but are not predictive in terms of cases etc.

3. Forward work programme

   - The Group endorsed the proposed priorities, in particular the focus on ensuring we understood health system constraints and what the benefit would be from increasing capacity in key areas

   - The Group also noted the need to take a 'data driven' approach to complement the modelling results. This includes understanding real world

outcomes e.g. in countries where vaccination is more advanced or new variants are present. **Action: George** to scope up options for a small piece of work to help understand international insights.

- The Group supported the proposal to establish a technical modelling group that would bring together all the modellers involved in COVID and create a forum for engaging on the technical issues and asking what the modellers think the priorities should be. The attached diagram thanks to Trish sets out the possible approach/relationships between groups.

- Next steps are to use this set of priorities to engage with TPM on priorities for a new contract, the wider modelling community and Tony Blakely.

Ngā mihi

Chris Nees| Principal Advisor | Economic Strategy Directorate |Te Tai Ōhanga – The Treasury
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-
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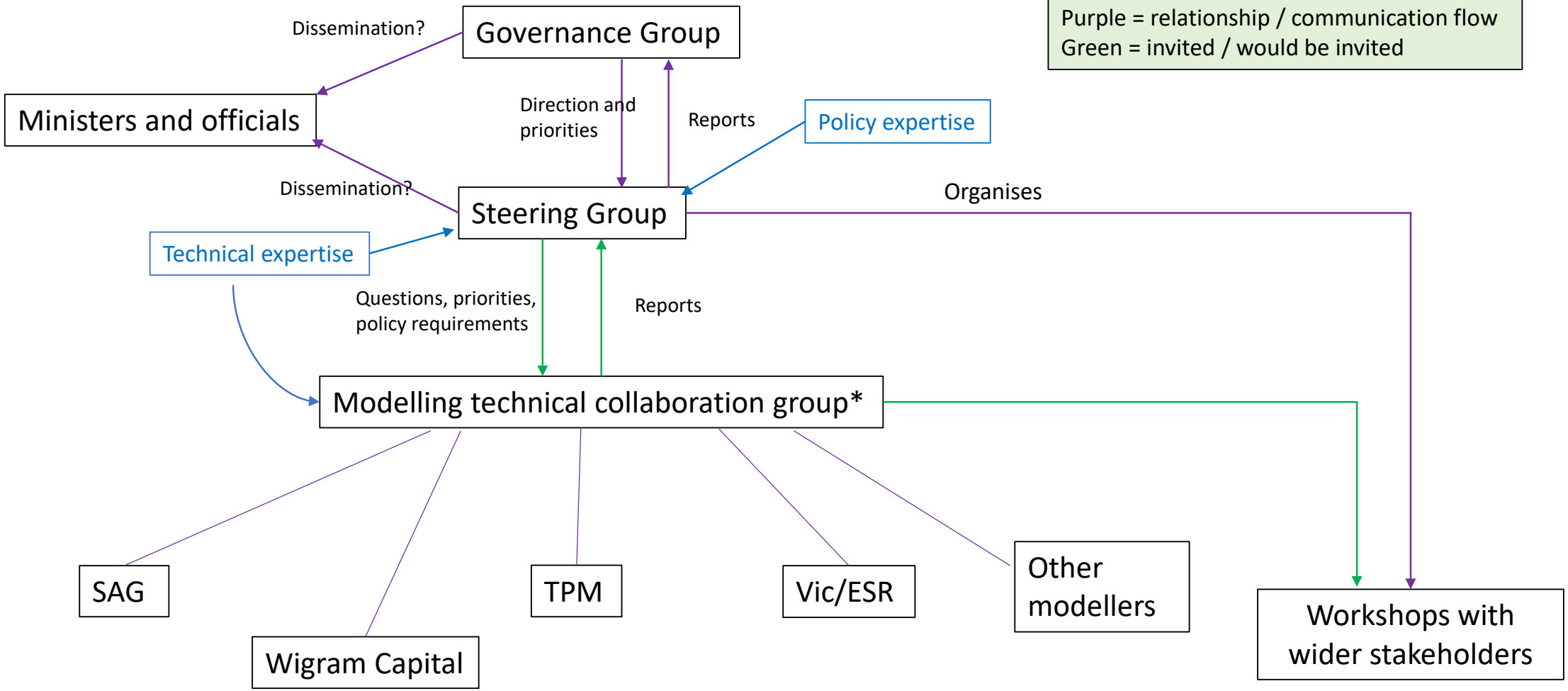
-

Possible future(?)
Purple = relationship / communication flow
Green = invited / would be invited



* Not its real name…

(NB funding removed from this diagram, but would be good to consider)

From:	Talosaga Talosaga
To:	Christopher Nees [TSY]; Bryan Chapple [TSY]; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; "x@x ; Ian Town; pmcsa; Susie Meade [DPMC]; Gill Hall; ^MBIE: Paul Stocks
Cc:	Margaret Galt [TSY]; "x@x ; Bevan Lye [TSY]; George Whitworth [DPMC]; Gill Hall; Kerryn Fowlie; Alastair Cameron [TSY]; Ryan Walsh [TSY]
Subject:	RE: Agenda and papers for Modelling Governance Group on Friday
Date:	Friday, 14 May 2021 2:48:21 PM
Attachments:	image001.png image002.png

FYI, some key takeaways from the TPM modelling that wrote earlier for a separate purpose. May be useful for the summary slides.

- Hospitalisation and fatality modelling results assume that all public health interventions are removed (no testing, no contact tracing, no isolation requirements for positive cases or international arrivals).
- Under this scenario, fatalities could range from 10 to 3000 depending on input assumptions.
- Based on current available information we cannot have confidence that vaccine coverage alone can prevent negative health outcomes, even with high coverage of a highly effective vaccine.
- This suggests that some bundle of public health interventions would be required in Phase 4, in order to avoid negative health outcomes.
- Further modelling and analysis will consider what this bundle of interventions may look like at different levels of population coverage.

Talosaga Talosaga | **Principal Policy Analyst** | Health Economics team | System Strategy and Policy |
Phone: s9(2)(k) | Email: xxxxxxxx.xxxxxxxx@xxxxxx.xxxx.xx

From: Christopher Nees [TSY] <xxxxx.xxxx@xxxxxxxx.xxxx.xx>
Sent: Tuesday, 11 May 2021 4:27 pm
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MSD: Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>; Cheryl Barnes [DPMC] <Cheryl.Barnes@dpmc.govt.nz>; 'xxxxx.xxxxxx@xxxxx.xxxx.xx' <xxxxx.xxxxxx@xxxxx.xxxx.xx>; Ian Town <Ian.xxxx@xxxxxx.xxxx.xx>; pmcsa <xxxxx@xxxxxxxx.xx.xx>; Susie Meade [DPMC] <xxxxx.xxxxx@xxxx.xxxx.nz>; Gill Hall <xxxx.xxxx@xxxxxx.xxxx.xx>; ^MBIE: Paul Stocks <xxxx.xxxxxx@xxxx.xxxx.xx>; Talosaga Talosaga <xxxxxxxx.xxxxxxxx@xxxxxx.xxxx.xx>
Cc: Margaret Galt [TSY] <xxxxxxxx.xxxx@xxxxxxxx.xxxx.xx>; 'Pubudu.Senanayakx@xxxxx.xxxx.xx' <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>; Bevan Lye [TSY] <Bevan.Lye@treasury.govt.nz>; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; Gill Hall <Gill.Hall@health.govt.nz>; Kerryn Fowlie <xxxxxx.xxxxxx@xxxxxxxx.xxxx.xx>; Alastair Cameron [TSY] <xxxxxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; Ryan Walsh [TSY] <Ryan.Walsh@treasury.govt.nz>
Subject: Agenda and papers for Modelling Governance Group on Friday

Kia ora koutou
Please find attached the agenda and papers for Friday's Modelling Governance Group meeting.

Ngā mihi

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I do not work on Thursdays.

-

From: Christopher Nees [TSY]
Sent: Wednesday, 5 May 2021 11:31 AM
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MSD: Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; 'xxxxx.xxxxxx@xxxxx.xxxx.xx' <xxxxx.xxxxxx@xxxxx.xxxx.xx>; 'xxx.xxxx@xxxxxx.xxxx.xx' <xxx.xxxx@xxxxxx.xxxx.xx>; 'xxxxx@xxxxxxxx.xx.xx' <xxxxx@xxxxxxxx.xx.xx>; Susie Meade [DPMC] <xxxxx.xxxxx@xxxx.xxxx.xx>; 'xxxx.xxxx@xxxxxx.xxxx.xx' <xxxx.xxxx@xxxxxx.xxxx.xx>; ^EDU: Paul Stocks; ^Health: Maree Roberts <xxxxx.xxxxxxx@xxxxxx.xxxx.xx>
Cc: Margaret Galt [TSY] <xxxxxxxx.xxxx@xxxxxxxx.xxxx.xx>; 'xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx' <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>; Bevan Lye [TSY] <xxxxx.xxx@xxxxxxxx.xxxx.xx>; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; 'xxxx.xxxx@xxxxxx.xxxx.xx' <xxxx.xxxx@xxxxxx.xxxx.xx>; Kerryn Fowlie <xxxxxx.xxxxxx@xxxxxxxx.xxxx.xx>; Alastair Cameron [TSY] <xxxxxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>
Subject: Draft proposed agenda for Covid-19 Modelling Governance Group next Friday

Kia ora koutou

Our proposed agenda for next Friday's Modelling Governance group is below – please let me know if there are other items you want to cover off and we will circulate a final agenda and papers on Monday:

1. Overview of vaccines/borders modelling results and next steps. We have been continuing to engage with TPM as they further develop the work we reported on at the last meeting. We'll cover key results and what is being commissioned from here, for your feedback and direction.

2. Latest context on the international picture. Through our contract with Wigram Capital, they have provided the Steering Group with an updated overview of the global picture looking at vaccine roll outs, effects on case numbers and fatalities, and unpicking the effect of lockdowns vs vaccination on those metrics. We have discussed a 'watch list' of issues to consider (e.g. how Israel's school reopening affects cases, how Sinovac is complicating the global picture, Singapore's continued community transmission, and how India looks to be bending the curve but another wave is inevitable). This is useful context to have in mind as we both consider vaccine efficacy in New Zealand and how borders re-open.

3. The Advisory Group – discussion on its operation and if/how we could support it further.

Ngā mihi

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-
I do not work on Thursdays.

-

-----Original Appointment-----
From: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx >
Sent: Friday, 16 April 2021 2:46 PM
To: Bryan Chapple [TSY]; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; 'vince.gxxxxx@xxxxx.xxxx.xx'; 'xxx.xxxx@xxxxxx.xxxx.xx'; 'xxxxx@xxxxxxxx.xx.xx'; Margaret Galt [TSY]; Christopher Nees [TSY]; George Whitworth [DPMC]; Susie Meade [DPMC]; Sam Tendeter [TSY]; 'xxxx.xxxx@xxxxxx.xxxx.xx'; 'xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx'; ^EDU: Paul Stocks; 'maree.roberts@health.govt.nz'
Subject: Covid-19 Modelling Governance Group
When: Friday, 14 May 2021 2:00 PM-2:45 PM (UTC+12:00) Auckland, Wellington.
Where: +TSY 3.34 Poutama -16 (EXT) - MS Teams Link enclosed

Dear attendees,

Agenda and papers will be circulated In advance.

Microsoft Teams meeting

Join on your computer or mobile app
Click here to join the meeting

Learn More | Meeting options

Kind Regards
Jozef

Jozef Citari | Te Tai Ōhanga - The Treasury
Executive Assistant to Deputy Secretary for Macroeconomics & Growth – Mr. Bryan Chapple

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From: George Whitworth [DPMC]
To: pmcsa; Bryan Chapple [TSY]; Ian Town; ^Health: Maree Roberts; Cheryl Barnes [DPMC]; ^MSD: Nic Blakeley; ^MBIE: Paul Stocks; "xxxxx.xxxxxx@xxxxx.xxxx.xx"
Cc: Ryan Walsh [TSY]; Christopher Nees [TSY]; Patricia Priest; xxxx.xxxx@xxxxxx.xxxx; Ruth Fairhall [DPMC]; ^EXT: Talosaga Talosaga; Pubudu Senanayake; Hamish Spencer; Samantha Fitch; Anna Ferguson [DPMC]; xxxxxxxx.xxxxxx@xxxxx.xx; Chris Knox
Subject: RE: Publication of TPM vaccination modelling
Date: Tuesday, 29 June 2021 5:58:35 PM
Attachments: image001.png
Report Vaccination Modelling within the International Context(4391517.3).pdf
Press release.docx

Good evening

Ahead of publication tomorrow, we have provided a briefing placing the vaccination modelling results against international insights. Attached here, for your information. Thanks to steering group colleagues in copy for some rapid feedback on a draft. Please do feel free to share the briefing with others in your agencies who might be interested, and we welcome any thoughts or comments. We anticipate this will be a fairly periodic theme of analysis going forward.

You will also find attached the final version of the press release that TPM are leading with tomorrow.

Thanks,

George

George Whitworth
Special Advisor, COVID-19 Group
Department of the Prime Minister and Cabinet

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E xx@xxx

From: George Whitworth [DPMC]
Sent: Tuesday, 22 June 2021 3:51 pm
To: 'Prime Minister's Chief Science Advisor' <xxxxx@xxxxxxxx.xx.xx>; Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; 'Ian Town' <xxx.xxxx@xxxxxx.xxxx.xx>; ^Health: Maree Roberts <xxxxx.xxxxxxx@xxxxxx.xxxx.xx>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; ^MSD: Nic Blakeley <xxx.xxxxxxxxxxx@xxx.xxvt.nz>; ^MBIE: Paul Stocks <xxxx.xxxxxx@xxxx.xxxx.xx>; 'xxxxx.xxxxxx@xxxxx.xxxx.xx' <xxxxx.xxxxxx@xxxxx.xxxx.xx>
Cc: Ryan Walsh [TSY] <xxxx.xxxxx@xxxxxxxx.xxxx.xx>; Christopher Nees [TSY] <xxxxx.xxxx@xxxxxxxx.xxxx.xx>; 'Patricia Priest' <Patricia.Priest@health.govt.nz>; xxxx.xxxx@xxxxxx.xxxx.xx; Ruth Fairhall [DPMC] <xxxx.xxxxxxxx@xxxx.xxxx.nz>; ^EXT: Talosaga Talosaga <xxxxxxxx.xxxxxxxx@xxxxxx.xxxx.xx>; Pubudu Senanayake <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>; Hamish Spencer <hamish.spencer@otago.ac.nz>; Samantha Fitch <xxxxxxxx.xxxxxxxx@xxx.xxxx.xx>

Subject: Publication of TPM vaccination modelling

[IN-CONFIDENCE]

Kia ora modelling governance group colleagues,

For your information, a few of us have just come off our regular call with Shaun and associated researchers. We discussed publication plans for the initial modelling results (as have been shared with yourselves, Ministers, and CCB this morning). By way of context, it's worth noting that Ashley and the PM had made public references to the modelling being undertaken, over the past week. This has generated some media interest in forthcoming publication of the material.

TPM plan to publish their initial paper/results next Wednesday, as this is when Shaun and Mike (Plank) have some diary availability for media engagement. They will share the papers with selected journalists in the Science Media Centre, under embargo, in order to allow for some informed coverage upon release.
I have asked Shaun to share the draft press release with us, so we can get sight of their leading messages, with as much notice as he is comfortable offering.

Off the back of the draft PR, we'll see whether we might provide any additional talking points for Ministers, beyond anything included in previous briefings. DPMC COVID-19 group are coordinating a short briefing which contrasts modelling results with overseas outcomes, which I expect will have some useful points to inform any public conversation on the results. We'll be consulting across the Modelling Steering Group on that material over the remainder of this week, and will share a final version with governance group colleagues.

Thanks – do let us know if any questions,

George

George Whitworth
Special Advisor, COVID-19 Group
Department of the Prime Minister and Cabinet

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DEPARTMENT OF THE PRIME MINISTER AND CABINET
TE TARI O TE PIRIMIA ME TE KOMITI MATUA

Briefing

VACCINATION MODELLING IN THE INTERNATIONAL CONTEXT

To: Rt Hon Jacinda Ardern
Prime Minister

Hon Chris Hipkins
Minister for COVID-19 Response

Hon Ayesha Verrall
Associate Minister of Health

Cc: Hon Grant Robertson
Minister of Finance

Date	29/06/2021	**Priority**	High
Deadline	30/06/2021	**Briefing Number**	DPMC-2020/21-1070

Purpose

1. The initial vaccination modelling by Te Pūnaha Matatini (TPM) will be published on Wednesday 30 June and the Institute for Environmental Science and Research (ESR) to be published later in July.

2. Following discussion of initial results (DPMC-2020/21-944 refers), Ministers and senior officials have expressed an interest in how modelling insights compare with real-world outcomes we are beginning to observe overseas. Publication of results may lead to public debate on this issue.

3. This briefing discusses international case studies, relating observable outcomes to the implications of the initial vaccination modelling results. We focus on countries which have either high rates of vaccination, recent notable community transmission events, or both.

Recommendations

1. **Note** that this briefing will be shared with the Strategic COVID-19 Public Health Advisory Group (chaired by Professor Sir David Skegg) and the Prime Minister's Chief Science Advisor, Professor Dame Juliet Gerrard.
2. **Note** the areas of focus for ongoing monitoring of international outcomes, including that DPMC and Ministry of Health officials are engaging with Singaporean officials to discover any further lessons on outbreak management in a partially vaccinated population.
3. **Agree** to forward this briefing to the members of the Ministerial COVID-19 Strategy Group. **YES / NO**
4. **Agree** that this briefing is proactively released, with any appropriate redaction where information would have been withheld under the Official Information Act 1982, in August 2021. **YES / NO**

pp Ben White Alice Hume **Manager, Strategy & Policy – COVID-19 Group**	Rt Hon Jacinda Ardern **Prime Minister**
21/6/2021	...../...../2021
Hon Chris Hipkins **Minister for COVID-19 Response**	Hon Ayesha Verrall **Associate Minister of Health**
...../...../2021	...../...../2021

Contact for telephone discussion if required:

Name	Position	Telephone		1st contact
Alice Hume	Manager, Strategy and Policy – COVID-19 Group	+64 21 632 665	+64 4 912 0591	✓
George Whitworth	Principal Policy Advisor	N/A	N/A	
Anna Ferguson	Policy Advisor	N/A	N/A	

Minister's office comments:

- ☐ Noted
- ☐ Seen
- ☐ Approved
- ☐ Needs change
- ☐ Withdrawn
- ☐ Not seen by Minister
- ☐ Overtaken by events
- ☐ Referred to

VACCINATION MODELLING IN THE INTERNATIONAL CONTEXT

Executive Summary

1. Reviewing COVID-19 outcomes overseas is a way to assess the validity of initial vaccination modelling results, such as those produced by Te Pūnaha Matatini (TPM) and the Institute for Environmental Science and Research (ESR). This briefing explores whether these real-world, international experiences are consistent with the conclusions drawn from these initial results.

2. New Zealand's COVID-19 experience is markedly different to most other countries. By pursuing an elimination strategy – effectively 'keeping it out' and 'stamping out' small clusters of COVID-19 as they arise in the community – we have a unique context in terms of what success looks like. Most other countries are unwilling to impose the restrictions that might enable them to achieve outcomes that remain realistic for New Zealand.

3. However, useful insights can be drawn from overseas experience to help us reflect on the results of the initial vaccination modelling. This briefing considers two categories of international comparators:

   a) countries with relatively high rates of vaccination, such as the UK and Israel, to assess conclusions on "population immunity" thresholds; and

   b) countries that have lower rates of vaccination and have suffered recent outbreaks, to assess outbreak dynamics in populations with mixed vaccination statuses.

4. In summary, real-world outcomes elsewhere align with, and do not give reason to doubt, the key messages from the initial vaccination modelling:

   a) **Population immunity will require very high levels of uptake, but the vaccines are effective at reducing harms to vaccinated individuals.** The overall vaccination rates in the UK, for instance, are insufficient to stop exponential, unlimited growth in case numbers – despite ongoing restrictions on the population. Recent data in Israel also supports this conclusion. The recent Singaporean outbreak has demonstrated the benefit of reduced harm for vaccinated individuals.

   b) **Concurrent public health controls will still be required at high levels of vaccination.** Israel, for example, still has strict "keep it out" border measures, as well as ongoing public health interventions and restrictions on daily life which are intended to safeguard against community transmission. This has enabled a sustained period with low numbers of new cases.

   c) **Vaccination will support efforts to "stamp it out" when cases do arise, but will have implications for how we manage outbreaks.** For instance, Singapore has recently successfully contained an outbreak, in which vaccination of affected individuals has supported control of the situation. However, it has also highlighted that vaccinated people can and do play a role in transmission of COVID-19. Vaccination might create challenges for detecting potential infections, particularly as symptoms are reduced in infected, vaccinated individuals who may still be able to transmit the virus.

Case Studies

5. New Zealand's elimination strategy approach to the management of the COVID-19 virus means we are almost uniquely placed in the world, as we look ahead to a strategy for *Reconnecting New Zealanders.* Few other countries have successfully maintained such low levels of COVID-19 within their community. We critically assess real-world outcomes in relation to this local context: what is deemed a successful outcome, or a tolerable risk, elsewhere might be considered a failure, or an unacceptable risk, for New Zealand.

6. Vaccination is just one tool of many in the COVID-19 management toolkit. By looking at a variety of jurisdictions with different epidemiological contexts and vaccination rates (summarised in Attachments A and B), we can:

   a) Refine our understanding of the validity and accuracy of the modelling undertaken to date; and

   b) Begin to "triangulate" on the best application of a suite of management tools to achieve the outcomes we desire – informing scenario selection for further, more sophisticated modelling currently underway.

7. Many countries are seeing vaccination as a tool reduce incidence or impacts where infection has been widespread. For New Zealand, along with some other countries (such as Australia and Singapore) vaccination is more important as a tool to prevent transmission in the first place.

Israel has achieved very low levels of community transmission in recent months. They have achieved high levels of vaccination, but the reduction in cases was achieved through ongoing population controls and restrictions on international travel.

8. Israel has taken a similar approach to vaccination as New Zealand: a single vaccine (Pfizer-BioNTech) administered with a 21-day second dose schedule. At 24 June 2021, about 59% of the population have received both doses of the Pfizer-BioNtech vaccine, which equates to around 80% of the population over the age of 12.

9. Israel started vaccinations in December 2020, when they were reporting a seven-day rolling average of around 2,400 new cases of COVID-19 a day. But by mid-January average cases were numbering over 8,600 cases a day.

   Internal restrictions in Israel have played an important role in containing COVID-19 transmission…

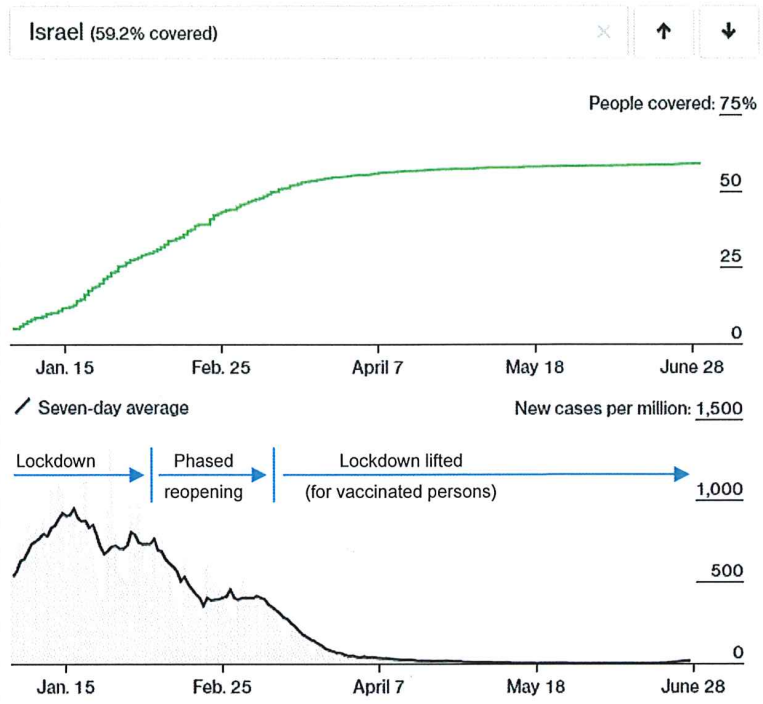
10. Israeli authorities imposed a third national lockdown, due to this 'third wave'. This lasted until early February 2021, when restrictions were lifted incrementally: some workplaces were able to operate if they did not receive customers; domestic travel restrictions lifted; and open-air parks were reopened

11. The greatest lifting of restrictions has prioritised those who are vaccinated. On 21 February 2021 the 'Green Pass' system allowed those who were fully vaccinated or had natural immunity to enter higher-risk locations, such as gyms, theatres, and synagogues. This system was in place until early June 2021 and allowed 'Green Pass' holders to have a greater level of freedom of movement, than their non-vaccinated peers, as restrictions eased further from March 2021 onward.

12. This meant the greatest freedoms were reserved for those with lower chances of becoming infected, or of passing on the virus if they were infected. This may have been a significant factor in the continuing downward trend in new cases observed through March and April 2021. The interaction between transmission and vaccination of sub-populations will be explored in future modelling work.

    …but stringent border controls have played a role, too - particularly as case numbers reduced to very low levels.

Figure 1: Vaccination and case rates in Israel, 2021



Note: "People covered" divides the doses administered for each vaccine type by the number of doses required for full vaccination. Vaccine data from Bloomberg's Covid-19 Tracker. Cases data: Johns Hopkins University.

13. In late December 2020, Israel began to restrict foreign travellers from entering. Tourists are largely restricted from entering. Entrants are required to present a negative pre-departure PCR test, undergo a PCR test on arrival, and spend time in isolation after arrival. This includes state-designated isolation facilities for arrivals from higher-risk countries. This will have limited the number of imported cases, an important enabler of keeping case numbers low in the domestic community.

However, vaccination rates are not high enough to prevent exponential growth in cases without other measures in place.

14. The combination (of domestic restrictions, border controls, and the vaccination rollout) resulted in the seven-day average reducing to around 15 cases per day, by early June 2021. More recently, new cases have been recorded at over 100 per day, with as many as 50% of new cases in the vaccinated population. Authorities are indicating that domestic controls (the "mask mandate", in particular) will be reintroduced if the situation continues to worsen.

15. The recent worsening of the domestic situation has also been despite international travel remaining heavily controlled. Authorities had aimed to allow tourists from low-risk countries to enter from 1 July 2021 without requiring isolation. However, in light of the recent worsening of the COVID-19, these plans have been postponed to at least 1 August 2021.

The United Kingdom has achieved a comparable level of vaccination to Israel but has been unable to achieve and maintain a low level of community transmission.

16. The United Kingdom (UK) began its vaccine roll out in early December 2020. Unlike Israel and New Zealand, the UK are using a variety of vaccines including Pfizer-BioNTech, Oxford-AstraZeneca, Moderna, and Janssen. They have also prioritised first doses, extending the time between doses from 3-4 weeks to 12, allowing them to provide more first doses in a shorter timeframe and thereby increasing the proportion of the population that have a lower level of protection. To date approximately 60% of the UK population have

received their first dose of the vaccine, with 45% fully vaccinated (which equates to around 80% and 60%, respectively, of people aged 18 and over).

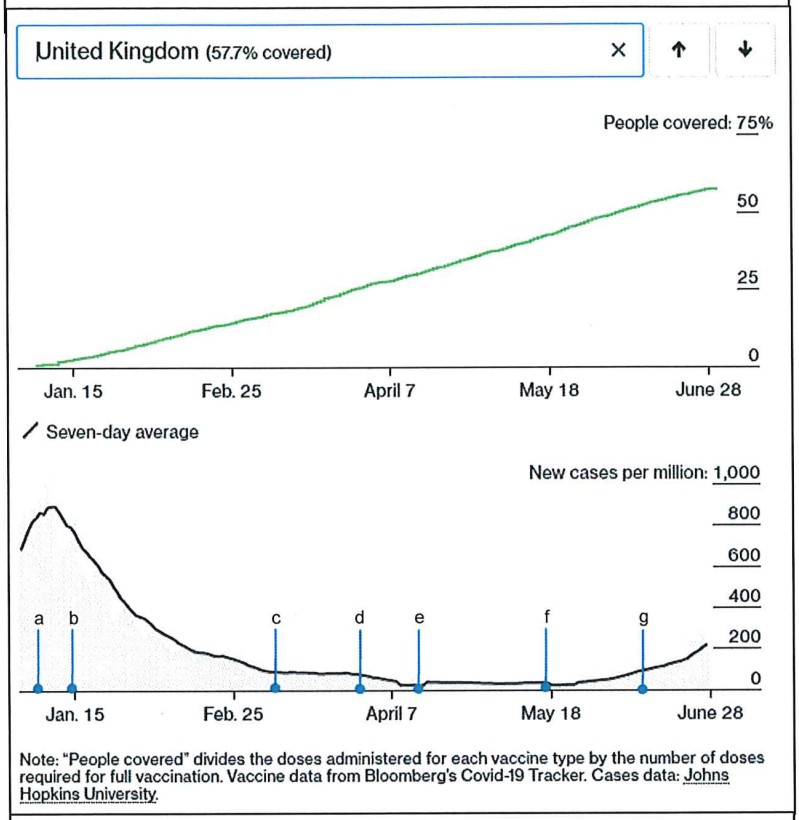
17. Following their winter, a "third wave" saw case numbers peak at up to 60,000 cases per day. A national lockdown meant new cases steadily fell to as low as 2,000 cases per day by May 2021.

18. Since March 2021, authorities have been taking a phased approach to lifting restrictions. The final step of the "roadmap for reopening" was due to take place on 21 June 2021, and would have lifted most population level restrictions on daily life.

19. However, this relaxation has been postponed: despite high levels of vaccination, the easing of restrictions saw case numbers increase rapidly. The seven-day average for new cases is above 10,000 per day, and recent estimates for R values have been significantly greater than 1 and increasing.

20. This rapid increase of cases is also occurring in a population which has been significantly more exposed to COVID-19 over the prior year. Past infection should confer some degree of protection for individuals and act to limit spread across the population. Confirmed cases account for 7% of the population, while Office of National Statistics (ONS) estimates suggest that as many as 10-15% of the population may have been exposed to COVID-19.

Figure 2: Vaccination and case rates in United Kingdom, 2021



Note: "People covered" divides the doses administered for each vaccine type by the number of doses required for full vaccination. Vaccine data from Bloomberg's Covid-19 Tracker. Cases data: Johns Hopkins University.

Response timeline: key phases/decisions:

a. UK in lockdown
b. From Jan: Travel bans from higher-risk countries introduced.
c. 8 March: Children return to school
d. 29 March: Stay-at-home order comes to an end
e. 12 April: Reopening of non-essential retail
f. 17 May: Pubs and restaurants reopen; indoor mixing allowed
g. 14 June: England's final relaxation of restrictions (planned for 21 June) will be delayed by four weeks, until 19 July.

21. These figures, combined with high vaccination rates, are evidently insufficient to stop exponential growth in cases, at least in some communities within the population. It is not clear yet how the recent increase in case numbers will translate into more severe outcomes, such as hospitalisation and fatality.

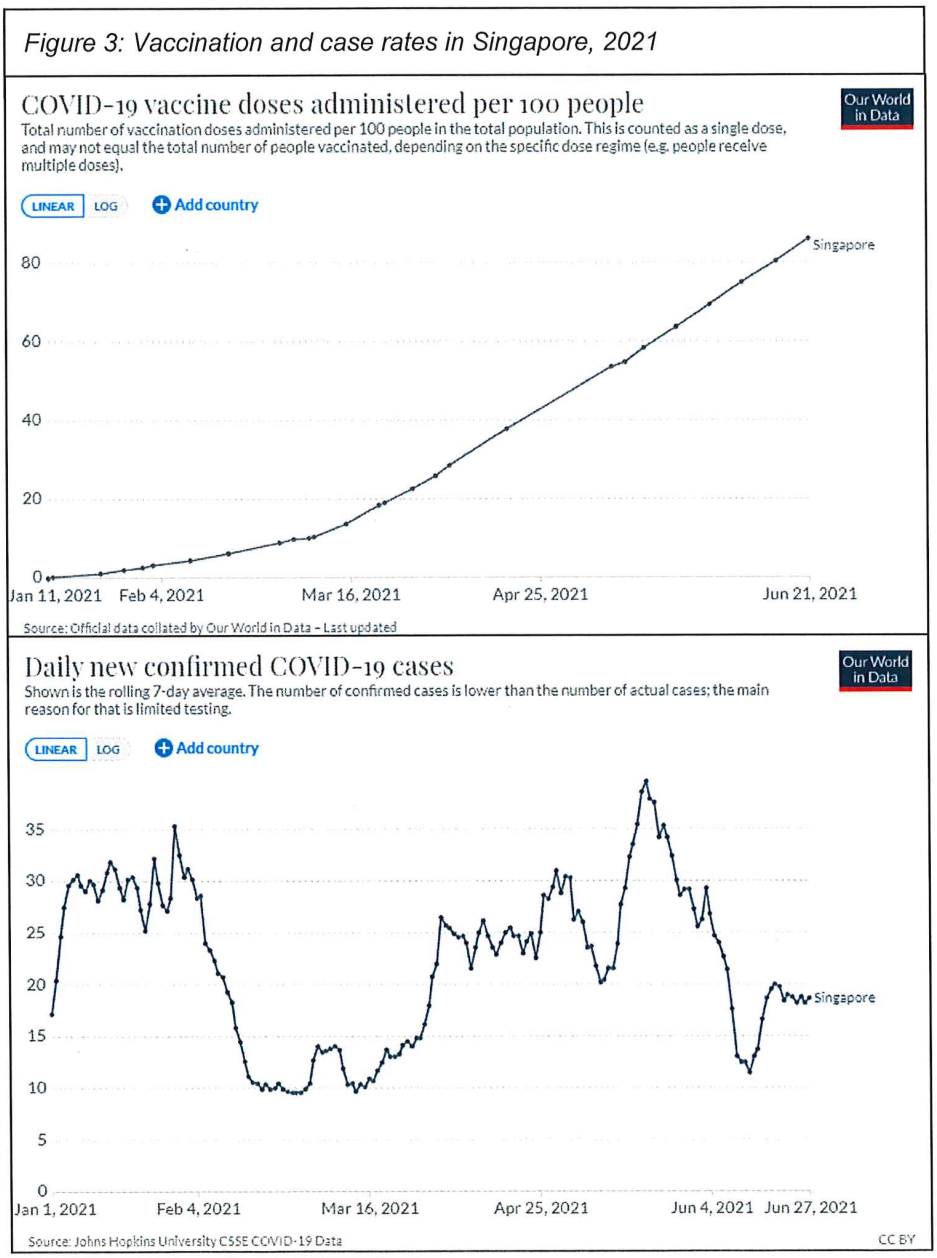
22. This suggests that even with levels of vaccination comparable to countries such as the UK, high numbers of cases are still a realistic possibility for New Zealand if domestic risk mitigate measures are removed. As discussed in interpretation of vaccination modelling results, high rates of vaccination in New Zealand are another 'string to the bow' of the elimination strategy, but are unlikely to be sufficient on their own to allow other risk mitigations to be removed completely.

Singapore is at an earlier stage in its vaccination rollout than the UK or Israel. Its domestic situation is more similar to New Zealand, with generally very low numbers of cases throughout the duration of the pandemic.[1]

23. Singapore has administered over 5 million doses of vaccines. Slightly more than 50% of the population have received the first dose of the vaccine, while about 36% of the population have received both doses. They are using Pfizer/BioNTech and Moderna vaccines and have good vaccination rates within those that work in high-risk settings (e.g hospitals and airports).

24. Singapore recently experienced an increase in community cases of COVID-19 which peaked in May 2021 with over 200 cases reported in a week. The vaccination programme was about half as advanced as it is now.

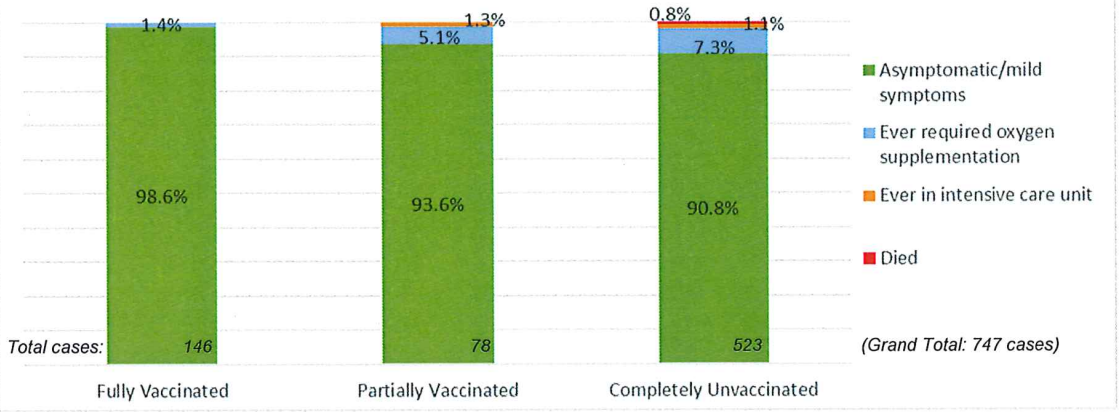
Figure 3: Vaccination and case rates in Singapore, 2021



[1] *This section draws on reporting from New Zealand's High Commission in Singapore.*

25. Despite vaccination, there were 146 fully vaccinated and 78 partially vaccinated individuals who tested positive for COVID-19. Over the course of the outbreak, around 1 case in every 6 were among the vaccinated. These individuals have experienced milder symptoms: only 2 fully vaccinated individuals (of 146) experienced a moderate case of COVID-19 (briefly requiring oxygen) and there have been no ICU admissions within this group. This contrasts with 44 (out of 523) unvaccinated individuals with more severe cases of COVID-19.

Figure 4: Breakdown of Local Singapore Cases Since 28 April by Vaccination Status and Severity of Condition



26. Transmission of the virus by vaccinated individuals is possible, and has been documented among household contacts. Singapore has not yet analysed the duration of infectivity among those who are fully vaccinated, nor observed any differences in transmission rates between Pfizer/BioNTech and Moderna vaccinations.

27. Singaporean officials expect that cases are more likely to be unlinked as a population becomes increasingly vaccinated, because any 'breakthrough' cases are likely to be asymptomatic or result only in mild illness.

28. Ministry of Health and DPMC officials will follow up with Singaporean officials to draw further insights which can be applied to outbreak management in a partially vaccinated population.

29. Singapore continues to follow a strict approach at the border to keep new cases of COVID-19 from entering the community.

The United States of America has some of the highest rates of vaccination in the world, but with significant differential in uptake within the population

30. With nearly half of the population fully vaccinated the United States of America (the US), has also seen significant decreases in new cases being reported. Beneath this high average vaccination rate there are significant disparities at the state level. Lower vaccine uptake is correlated with a variety of factors: these states are more likely to be rural, have state governments that implemented limited risk mitigations, and have lower compliance with other public health measures. Many of these factors also correlate with citizens' political preferences.

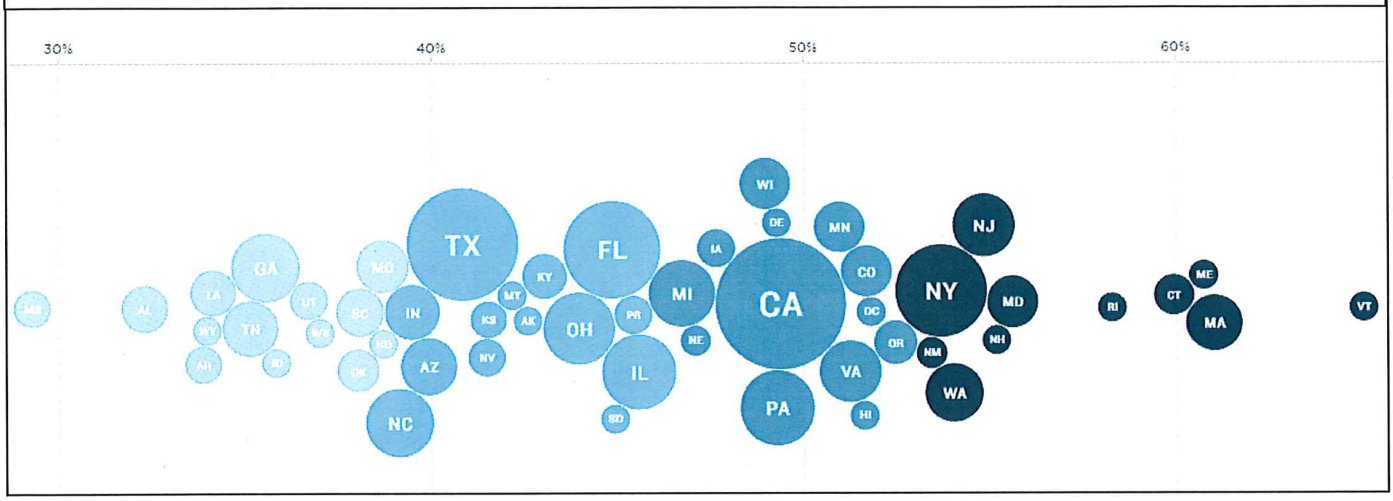
31. A peak of over 300,000 cases reported on the 8th of January 2021 has decreased to a rolling 7-day average of around 14,000 new cases by June 2021. In March 2021, the CDC estimated that as many as 35% of the population of the US have been infected with COVID-19 since the beginning of the pandemic; natural immunity, alongside the immunisation

rollout, may have played a role in limiting community transmission without the implementation of tight restrictions – but a range of restrictions have remained in place, many at the state level.

32. Looking ahead, we would expect differential vaccination rates to lead to different transmission dynamics at the state-level. This may have implications for how we consider the risk of travellers from the US, given the heterogeneity in the degree of population protection we would expect.

Figure 5: Percentage of state's population fully vaccinated, 27 June. Size of circle represents state's population size.

Source: CDC. Visualisation: NPR



Summary and Next Steps

33. Officials do not consider there to be international evidence that refutes the key conclusions of the vaccination modelling we have seen to date. Indeed, there is emerging evidence which supports the key messages:

    a) Population immunity (without public health controls in place) is likely to require a very high rate of vaccination.

    b) We will continue to need risk mitigation measures in place at the border and in the community, and our calibration of these measures may need to change as vaccination rates increase.

34. Israel and Singapore have implemented a range of risk mitigation measures similar to those used within New Zealand as part of the elimination strategy, including border restrictions, PCR testing, isolation of high-risk travellers. Both have also used mask mandates to help reduce the spread of variants of concern within their communities.

35. The modelling steering group will continue to monitor international developments and consider modelling outputs in that context. There are four areas of interest as further data emerges:

    a) Given high and increasing rates of vaccination in some adult populations – particularly in the UK and Israel - can we learn more about the susceptibility of children, their role in transmission and, hence, their importance for building population protection?

b) As countries and regions with different rates of vaccination experience outbreaks, can we learn more about outbreak dynamics and the interventions required to control outbreaks at different points of the vaccine rollout, by:

   i) comparing non-pharmaceutical interventions required to minimise transmission within similarly vaccinated populations? *and*

   ii) comparing the same non-pharmaceutical interventions when applied to different populations with significantly different rates of vaccination?

c) Officials of the Ministry of Health and DPMC will meet with Singaporean officials to gather further insights regarding outbreak management in a partially vaccinated population, given the relatively similar epidemiological context and objectives.

d) How does the relationship between case numbers and hospitalisations or fatalities evolve in highly vaccinated populations with sustained transmission of COVID-19, such as the UK?

Consultation

36. Officials from the Modelling Steering Group were consulted in generating this briefing, which includes the Ministry of Health, Department of the Prime Minister and Cabinet, StatsNZ, the Treasury, Ministry of Business, Innovation and Employment and the Ministry of Social Development.

37. This briefing draws on open source material and conversations with/reporting from New Zealand's High Commission in Singapore, the Prime Minister's Chief Science Advisor (and team) and Rodney Jones (Wigram Capital).

Communications

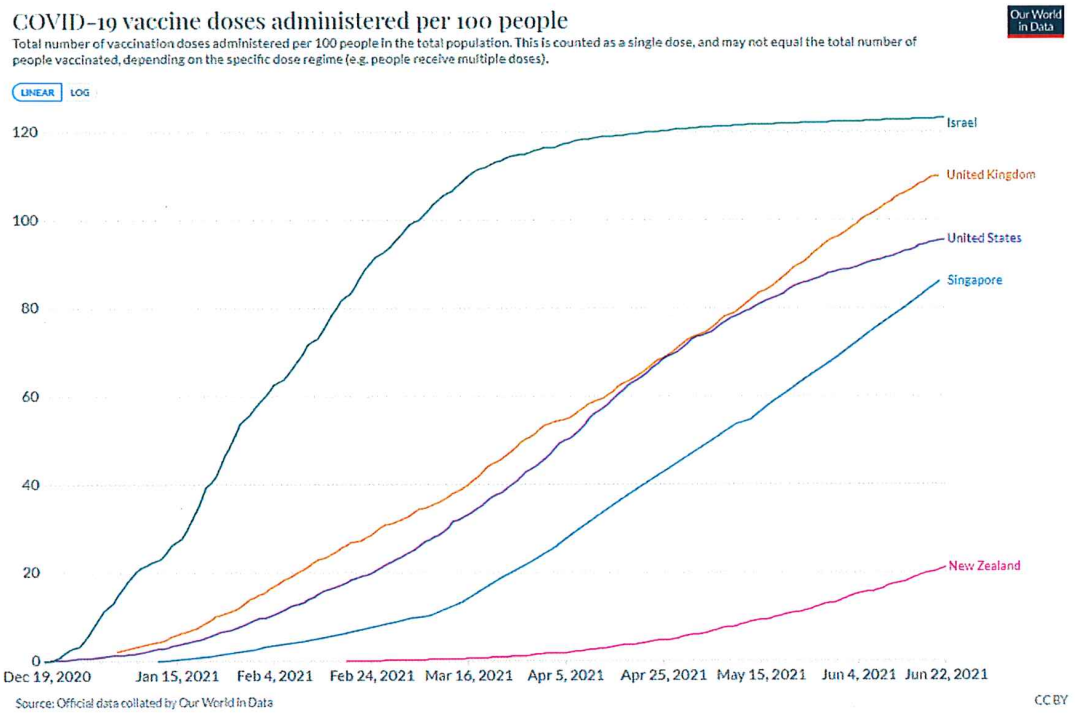
38. There are no direct communications implications arising from this briefing.

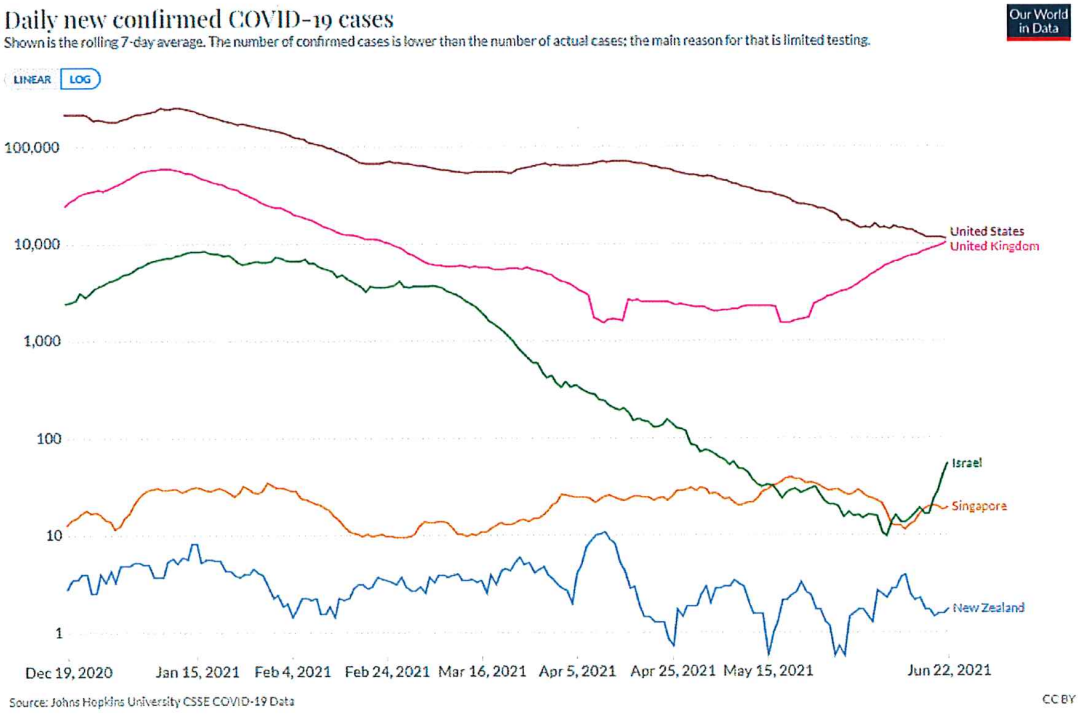
39. The content of this briefing may be useful if questions arise following the publication of initial modelling results by Te Pūnaha Matatini on Wednesday 30 June 2021.

[IN-CONFIDENCE]

ATTACHMENT A

Vaccination rates, cases, deaths, restrictions in selected countries





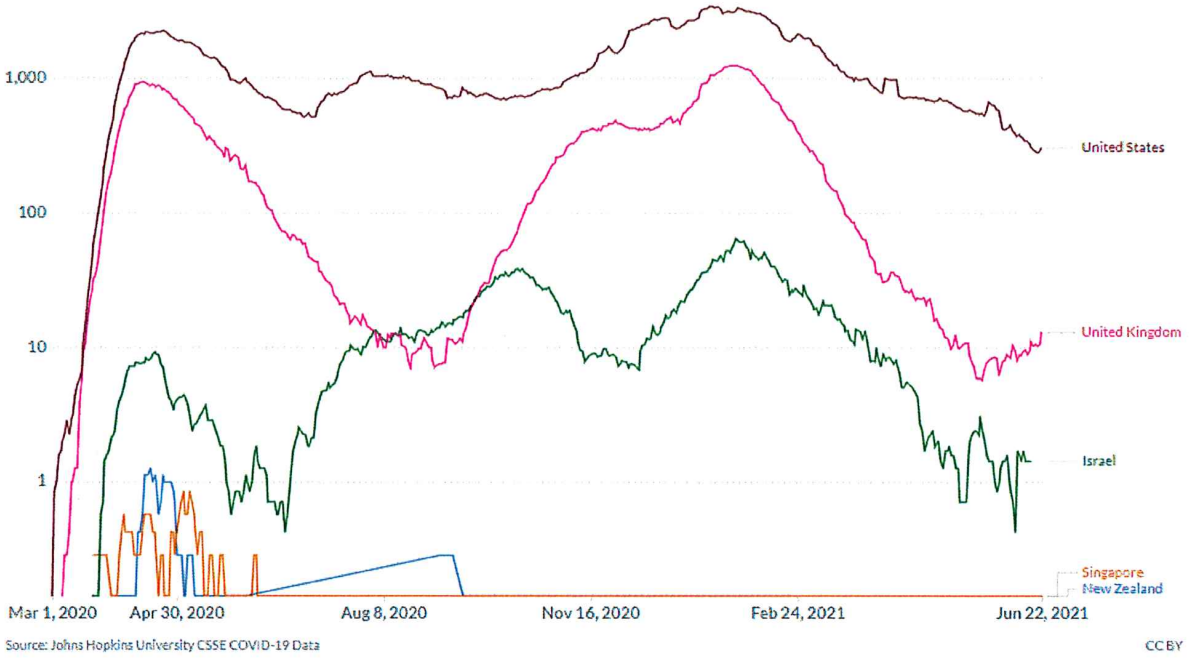
[IN-CONFIDENCE]

Daily new confirmed COVID-19 deaths

Shown is the rolling 7-day average. Limited testing and challenges in the attribution of the cause of death means that the number of confirmed deaths may not be an accurate count of the true number of deaths from COVID-19.

Our World in Data

LINEAR LOG



Source: Johns Hopkins University CSSE COVID-19 Data

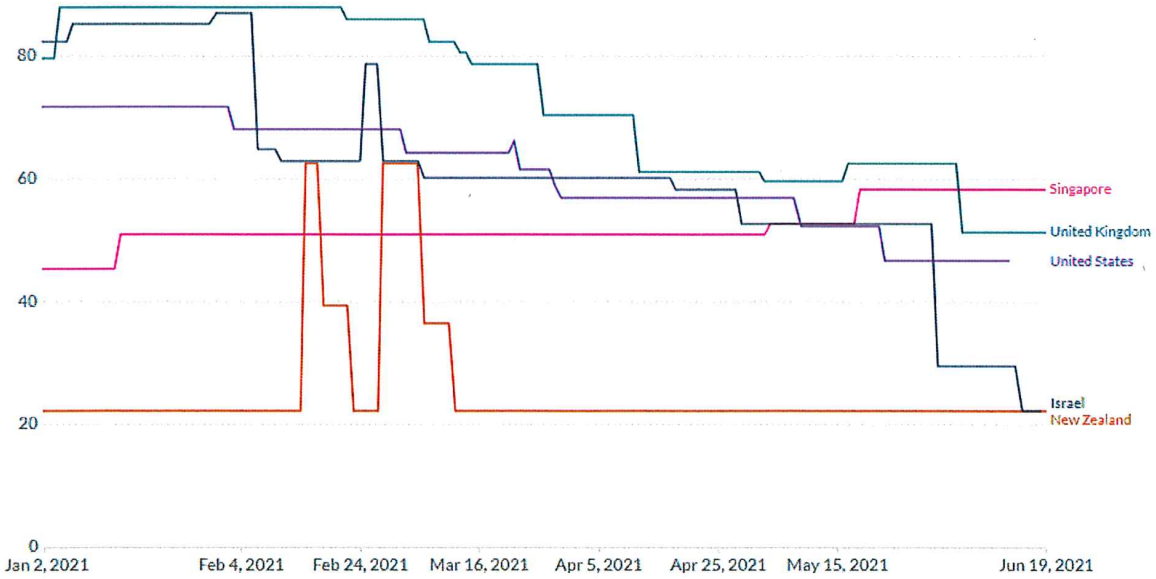
CC BY

COVID-19: Stringency Index

This is a composite measure based on nine response indicators including school closures, workplace closures, and travel bans, rescaled to a value from 0 to 100 (100 = strictest). If policies vary at the subnational level, the index is shown as the response level of the strictest sub-region.

Our World in Data

Add country



DEPARTMENT OF THE PRIME MINISTER AND CABINET
TE TARI O TE PIRIMIA ME TE KOMITI MATUA

ATTACHMENT B

Table of Vaccination and New Case Rates of Jurisdictions Reviewed in this Paper

Country *(vaccines used)*	**Population partially vaccinated (%)**	**Population fully vaccinated (%)**	**People aged 12+ with first dose (%)**	**People aged 12+ with second dose (%)**	**New cases, June 2021 daily average**	**New cases per million, June 2021 daily average**
Israel *(Pfizer-BioNTech)*	61.3	57.0	82.8	77.1	52	6
United Kingdom *(Pfizer-BioNTech, Moderna, Astrazeneca, Janssen, Novavax)*	66.3	48.6	75.7	55.3	8876	131
USA *(Pfizer-BioNTech, Moderna, Janssen)*	54.0	46.1	63.2	50.6	13615	41
Singapore *(Pfizer-BioNTech, Moderna)*	52.1	36.1	56.3	39.0	18	3
New Zealand *(Pfizer-BioNTech)*	13.0	7.7	15.6	9.4	2	0.5
Source (at 28 June)	*Bloomberg vaccine tracker*	*Bloomberg vaccine tracker*	*The Economist*	*The Economist*	*Our world in data*	*Our world in data*

Te Pūnaha Matatini
Data ▪ Knowledge ▪ Insight

Modelling suggests that public health measures will need to remain in place for duration of vaccine rollout

Under embargo until 0100 on Wednesday 30 June 2021 (NZ time)

New modelling from Te Pūnaha Matatini has shown that public health measures will need to remain in place for the entire duration of Aotearoa New Zealand's vaccine rollout to avoid hospitalisations and fatalities from COVID-19 outbreaks.

But lead author Nic Steyn says that the good news is "increasing levels of vaccination will make maintaining an elimination strategy easier and allow the country to eventually move from relying on population-wide interventions like lockdowns to more targeted controls like contact tracing in the later stages of the rollout."

"We're going to need to use the vaccine in conjunction with the other layers of protection that we have at the moment," says Professor Michael Plank. "This means that border restrictions, the Alert Level system, community testing and contact tracing will need to remain in place."

The team used an age-structured model of COVID-19 transmission in Aotearoa New Zealand to estimate how increasing levels of immunity through vaccination can slow the growth of an outbreak. The models combined the latest available data on vaccine effectiveness with social contact survey data that estimates how much contact there is between people in different age groups across the country.

This modelling provides an indication of the potential for spread at a broad-scale national level and includes a range of scenarios at various stages of the vaccine rollout, from contained local outbreaks to an unmitigated epidemic.

Professor Shaun Hendy says that "we're still vulnerable to COVID-19 and will remain vulnerable even once the vaccine rollout is complete, but the results show that things will get better as the rollout progresses."

This modelling also includes the first New Zealand-specific estimates of the percentage of the population that needs to be vaccinated to reach population immunity. The lowest estimate of the population immunity threshold that the models produced was an 83% vaccination rate across the total population. This was based on data from older variants of the virus with an estimated basic reproduction number of 4.5 and assuming the vaccine reduces transmission by 85%. Emerging data on newer more transmissible variants suggests a higher threshold, although this remains uncertain.

"Until we get close to that threshold we are still at risk of a significant health impact from an outbreak that would include overwhelming our healthcare capacity," says Hendy.

"While the rollout is still underway, the elimination strategy gives us the best options for controlling any outbreaks and protecting people who haven't yet been vaccinated."

Te Pūnaha Matatini
Data ▪ Knowledge ▪ Insight

Vaccination rates will vary across Aotearoa New Zealand, so even if population immunity is reached nationally, communities with vaccination rates lower than the national average will remain at risk of hospitalisation and fatalities from COVID-19 outbreaks. Further modelling work will be needed to investigate this.

Professor Michael Plank cautions that “we’re not going to one day magically hit a population immunity threshold where we can open the borders and everything goes completely back to normal. It will be more of a gradual relaxation of border measures alongside continued testing and contact tracing measures.”

“If we relax border restrictions, we will see COVID-19 cases and it’s quite likely that we’ll see outbreaks. The way to protect against those outbreaks is to get vaccinated.”

There is still a lot to learn about the Pfizer vaccine and its effectiveness in different population groups. These models will need to be updated as new data is collected internationally about vaccine effectiveness and transmissibility of new variants.

Plank says that these results deliver a clear message: “As more of the population gets vaccinated, we still need to go as hard as we’ve ever done on testing, contact tracing, scanning in, hand sanitising and wearing masks.”

“The vaccine rollout is good news,” says Hendy, “but life is not going back to normal for some time.”

Note: this research has been released as a pre-print and has not yet been formally peer reviewed.

Under embargo until 0100 on Wednesday 30 June 2021 (NZ time)

Media contact

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To:	Bryan Chapple [TSY]; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; "xxxxx.xxxxxx@xxxxx.xxxx.xx" "xxx.xxxx@xxxxxx.xxxx.xx"; "xxxxx@xxxxxxxx.xx.xx" ; Susie Meade [DPMC]; "xxxx.xxxx@xxxxxx.xxxx.xx" ^EDU: Paul Stocks; ^Health: Maree Roberts
Cc:	Margaret Galt [TSY]; "xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx" ; Bevan Lye [TSY]; George Whitworth [DPMC]; "xxxx.xxxx@xxxxxx.xxxx.xx"; Kerryn Fowlie; Alastair Cameron [TSY]
Subject:	Draft proposed agenda for Covid-19 Modelling Governance Group next Friday
Date:	Wednesday, 5 May 2021 11:30:00 AM
Attachments:	image001.png image002.png

Kia ora koutou

Our proposed agenda for next Friday's Modelling Governance group is below – please let me know if there are other items you want to cover off and we will circulate a final agenda and papers on Monday:

1. Overview of vaccines/borders modelling results and next steps. We have been continuing to engage with TPM as they further develop the work we reported on at the last meeting. We'll cover key results and what is being commissioned from here, for your feedback and direction.

2. Latest context on the international picture. Through our contract with Wigram Capital, they have provided the Steering Group with an updated overview of the global picture looking at vaccine roll outs, effects on case numbers and fatalities, and unpicking the effect of lockdowns vs vaccination on those metrics. We have discussed a 'watch list' of issues to consider (e.g. how Israel's school reopening affects cases, how Sinovac is complicating the global picture, Singapore's continued community transmission, and how India looks to be bending the curve but another wave is inevitable). This is useful context to have in mind as we both consider vaccine efficacy in New Zealand and how borders re-open.

3. The Advisory Group – discussion on its operation and if/how we could support it further.

Ngā mihi

Chris Nees| Principal Advisor | Economic Strategy Directorate |Te Tai Ōhanga – The Treasury
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Visit us online at https://treasury.govt.nz/ and follow us on Twitter, LinkedIn and Instagram

-
I do not work on Thursdays.

-

-----Original Appointment-----
From: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>
Sent: Friday, 16 April 2021 2:46 PM
To: Bryan Chapple [TSY]; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; 'vince.gxxxxx@xxxxx.xxxx.xx'; 'xxx.xxxx@xxxxxx.xxxx.xx'; 'xxxxx@xxxxxxxx.xx.xx'; Margaret Galt [TSY]; Christopher Nees [TSY]; George Whitworth [DPMC]; Susie Meade [DPMC]; Sam Tendeter [TSY]; 'Gill.Hxxx@xxxxxx.xxxx.xx'; 'xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx'; ^EDU: Paul Stocks; 'maree.roberts@health.govt.nz'
Subject: Covid-19 Modelling Governance Group
When: Friday, 14 May 2021 2:00 PM-2:45 PM (UTC+12:00) Auckland, Wellington.
Where: +TSY 3.34 Poutama -16 (EXT) - MS Teams Link enclosed

Dear attendees,

Agenda and papers will be circulated In advance.

Microsoft Teams meeting

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Kind Regards
Jozef

Jozef Citari | Te Tai Ōhanga - The Treasury
Executive Assistant to Deputy Secretary for Macroeconomics & Growth – Mr. Bryan Chapple

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Visit us online at https://treasury.govt.nz/ and follow us on Twitter, LinkedIn and Instagram

From:	Vince Galvin
To:	^MSD: Nic Blakeley; Christopher Nees [TSY]; Bryan Chapple [TSY]; ^MBIE: Paul Stocks; Cheryl Barnes [DPMC]; Ian Town; pmcsa; ^Health: Maree Roberts; Susie Meade
Cc:	Margaret Galt [TSY]; Gill Hall; George Whitworth [DPMC]; Pubudu Senanayake; Morag Hatcher; Sam Tendeter [TSY]; Patricia Priest; Kerryn Fowlie; Alastair Cameron [TSY]; ^EXT: Steven Sue
Subject:	RE: Draft Agenda for 12 April COVID-19 Modelling Governance Group
Date:	Wednesday, 14 April 2021 8:25:38 PM
Attachments:	image002.png image003.png

Kia Ora Koutou

Same spirit as Nic and thank you Trish for the responses– some observations from me;

- **Strengths and Weaknesses of Models** There was a statement about the stochastic models underestimating the impacts of the interventions. My understanding of the SEIR models is that they don't really estimate the impact of interventions. While we can model things like the way contact tracing plays out in detection this lasts for as long as there is no significant change in the rate at which people are in contact with each other. The problem I thought I understood was that after a change of level type of intervention is made we basically decide what the new R is and depending on what we assume we may need another round of assumptions about what the next interventions will be and how effective they will be. The underlying assumptions at different time points determine the results, so I think this limitation needs to be expressed slightly differently.

- **Impact of Border Opening**. I think the value of this analysis is in illustrating how different the input parameters have to be to produce an outcome in a different order of magnitude. The Optimistic and Realistic values are the same scale of adverse event but the input assumptions that lead to the significantly worse Pessimistic scenario don't seem that much of a deterioration from the other input assumptions. I like the idea of constructing a "surface" of these scenarios to illustrate what the best understanding is of what sorts of situations might lead to significant deterioration.

I found the discussion about the differences between the models very helpful. There are considerable subtleties to convey. The skew distribution of whether transmission actually occurs or not is very difficult to illustrate. Presenting distributional information often makes information displays complicated but it is a fundamental feature of pre-outbreak planning so I'm all for persisting with it.

Cheers

Vince

From: Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>
Sent: Monday, 12 April 2021 1:16 PM
To: Christopher Nees [TSY] <xxxxx.xxxx@xxxxxxxx.xxxx.xx>; Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MBIE: Paul Stocks <Paul.Stocks@mbie.govt.nz>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; Vince Galvin <vince.galvin@stats.govt.nz>; Ian Town <xxx.xxxx@xxxxxx.xxxx.xx>; pmcsa <xxxxx@xxxxxxxx.xx.xx>; ^Health: Maree Roberts <xxxxx.xxxxxxx@xxxxxx.xxxx.xx>; Susie Meade <xxxxx.xxxxx@xxxxxxxx.xx.xx>

Cc: xxxxxxxx.xxxx@xxxxxxxx.xxxx.xx; Gill Hall <xxxx.xxxx@xxxxxx.xxxx.xx>; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; Pubudu Senanayake <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>; Morag Hatcher <Morag.Hatcher@health.govt.nz>; Sam Tendeter [TSY] <xxx.xxxxxxxx@xxxxxxxx.xxxx.xx>; Patricia Priest <xxxxxxxx.xxxxxx@xxxxxx.xxxx.xx>; Kerryn Fowlie <Kerryn.Fowlie@treasury.govt.nz>; Alastair Cameron [TSY] <xxxxxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; Steven Sue <xxxxxx.xxxxxx@xxx.xxxx.xx>
Subject: RE: Draft Agenda for 12 April COVID-19 Modelling Governance Group

Kia ora koutou

Given today's meeting has been cancelled, I thought I'd send through a couple of points/questions I had:

- **Impact of border re-opening: equity impacts.** The A3 summarising the modelling for policy generally looked sensible to me and the right analysis to inform the key policy question this year. But analysis of equity impacts seemed light. There is one bullet point on impacts on groups who might face higher risk, but that's a subset of the equity issues to me. For example, differential vaccine uptake (by region/ethnicity/etc.) will have significant implications for where the burden of potential cases and deaths would fall, regardless of whether they are in higher risk groups from a straight health perspective (which will be more by age or co-morbidities). The modelling may not be able to get that sophisticated to actually model this type of equity impact, but it doesn't need to be that sophisticated (e.g. two types of population groups, one with lower vaccine uptake than the other). It would be worth exploring more what's possible.

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Ngā mihi

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Subject:	RE: Draft Agenda for 12 April COVID-19 Modelling Governance Group
Date:	Tuesday, 13 April 2021 1:02:29 PM
Attachments:	image001.png image002.png image003.png

Kia ora koutou

I know I'm not on the Governance Group, but I'm on this email list because I was going to attend yesterday's meeting on Ian's behalf so will take the opportunity to add some responses in Nic's text below. I hope my comments are helpful.

Kā mhi

Trish

From: Ian Town <xxx.xxxx@xxxxxx.xxxx.xx>

…

Dear Colleagues

Many thanks indeed Nic for those useful comments.

Modelling work around border opening would benefit from further discussion – like you the pessimistic scenarios can be galvanising but can also be unhelpful. The idea that there would not be an immediate Public health response to reduce R0 need to be woven into the interpretation of the information

Good discussion about the DPMC/MoH work on border opening would be a great next step.

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From: Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>

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The modelling may not be able to get that sophisticated to actually model this type of equity impact, but it doesn't need to be that sophisticated (e.g. two types of population groups, one with lower vaccine uptake than the other). It would be worth exploring more what's possible.

The questions on the A3 are intended to be a starting point. In the first instance we will be able to use the separate models for different levels of vaccine uptake (which have been conceptualised as stages through the vaccine rollout) to inform us about the implications for different regions with different uptake. The Network Model would be able to go further and model the impact of interactions between regions with greater and less coverage, and where the burden would sit.

- **Impact of border re-opening: early results.** The TPM paper is fascinating/scary. I wonder if Ministers and the public will have in mind yet that it's quite likely we have more cases/deaths in the next phase than we did in 2020. Table 3 is useful, but it would be useful to get a better understanding of the sensitivity on the key assumptions/judgements. I imagine the 90% vaccination assumption is a uniform distribution assumption? In reality, that won't be the case, so how might that play out differently if there were pockets of lower uptake (which links to my equity point above). The average results could end up with a false sense of security. I also wondered about the assumption of case fatality rate: it's based on the literature, but this has been improving over time as people learn more about how to treat it. I don't think there is any assumption about hospital capacity constraints? (e.g. the pessimistic scenario!) This analysis is really useful, but we need to dig into some of this so that when we present it to Ministers, they can see the range of potential outcomes.

The Steering group will be looking at and summarising the latest results from the initial vaccine modelling in the next few days. The message about the likelihood of more cases/deaths in the next phase is very important and conveying it to Ministers and the public will need to be done carefully but soon!

- **Use of modelling: guiding choices.** I generally agreed with the note on when modelling is useful. I'd emphasise the point in 'preparing for an outbreak' about informing choices on interventions. For example the TPM paper asserts that other things equal, it's better to have higher vaccination rates in higher risk groups. That's pretty intuitive at one level, but does take you to vaccine strategy that emphasises take-up rates in those groups, rather than take-up rates on average or in particular geographic regions? i.e. we want to use the results of the modelling to draw out implications for policy/strategy in the meantime, not just on the re-opening choice.

I absolutely agree that it's important that the modelling, with appropriate interpretation and caveats and brought together with other knowledge, informs policy/strategy in a timely way (i.e. in advance). I think a key challenge here is bringing together the people who have the range of skills and expertise to interpret the different sources of information and the authority to influence the policy/strategy-making process. Presumably that's you (Governance Group), informed by us (Steering Group)? Or perhaps the new Ministerial advisory group.

Nic

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Chief Clinical Advisor, Epidemiology
COVID-19 Science and Insights
COVID-19 Health System Response
Ministry of Health

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immediately and delete this message.
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Attachments:	image001.png image002.png Outlook-OPMCSA-log.png

Hi all

I'd support Nic's points.

Re the 'when to use the models' paper, I agree that it is useful and wondered whether Rodney and Shaun had reviewed it?

Re the vaccine and border opening work - just drawing your attention to the work of Tony Blakely in Melbourne below (with apologies to those to whom I already circulated this). The model is different but the conclusions are similar to the papers we were circulated.

'This is a new tool developed by the University of Melbourne for exploring COVID-19 policy responses (restrictions, vaccination roll-out, and border opening) - the slide deck is probably the simplest entry point:

https://populationinterventions.science.unimelb.edu.au/pandemic-trade-offs/

I like the focus on the interaction of different variables, including explicit options for relaxing from an elimination strategy, and how this plays out at different vaccination levels.'

cheers

Juliet

.....

Professor Dame Juliet A. Gerrard DNZM HonFRSC FRSNZ
Prime Minister's Chief Science Advisor
Kaitohutohu Mātanga Pūtaiao Matua ki te Pirimia

Office: 1-11 Short Street, Auckland 1010
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Read our annual report: https://www.pmcsa.ac.nz/2020/07/10/mahi-tahi-2-our-second-annual-report-is-ready-to-download/

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Given today's meeting has been cancelled, I thought I'd send through a couple of points/questions I had:

- **Impact of border re-opening: equity impacts.** The A3 summarising the modelling for policy generally looked sensible to me and the right analysis to inform the key policy question this year. But analysis of equity impacts seemed light. There is one bullet point on impacts on groups who might face higher risk, but that's a subset of the equity issues to me. For example, differential vaccine uptake (by region/ethnicity/etc.) will have significant implications for where the burden of potential cases and deaths would fall, regardless of whether they are in higher risk groups from a straight health perspective (which will be more by age or co-morbidities). The modelling may not be able to get that sophisticated to actually model this type of equity impact, but it doesn't need to be that sophisticated (e.g. two types of population groups, one with lower vaccine uptake than the other). It would be worth exploring more what's possible.

- **Impact of border re-opening: early results.** The TPM paper is fascinating/scary. I wonder if Ministers and the public will have in mind yet that it's quite likely we have more cases/deaths in the next phase than we did in 2020. Table 3 is useful, but it would be useful to get a better understanding of the sensitivity on the key assumptions/judgements. I imagine the 90% vaccination assumption is a uniform distribution assumption? In reality, that won't be the case, so how might that play out differently if there were pockets of lower uptake (which links to my equity point above). The average results could end up with a false sense of security. I also wondered about the assumption of case fatality rate: it's based on the literature, but this has been improving over time as people learn more about how to treat it. I don't think there is any assumption about hospital capacity constraints? (e.g. the pessimistic scenario!) This analysis is really useful, but we need to dig into some of this so that when we present it to Ministers, they can see the range of potential outcomes.

- **Use of modelling: guiding choices.** I generally agreed with the note on when modelling is useful. I'd emphasise the point in 'preparing for an outbreak' about informing choices on interventions. For example the TPM paper asserts that other things equal, it's better to have higher vaccination rates in higher risk groups. That's pretty intuitive at one level, but does take you to vaccine strategy that emphasises take-up rates in those groups, rather than take-up rates on average or in particular geographic regions? i.e. we want to use the results of the modelling to draw out implications for policy/strategy in the meantime, not just on the re-opening choice.

Nic

Nic Blakeley (he/him)
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From: Christopher Nees [TSY] <xxxxx.xxxx@xxxxxxxx.xxxx.xx>
Sent: Friday, 9 April 2021 4:15 PM
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>; ^MBIE: Paul Stocks <xxxx.xxxxxx@xxxx.xxxx.nz>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; xxxxx.xxxxxx@xxxxx.xxxx.xx; Ian Town <xxx.xxxx@xxxxxx.xxxx.xx>; pmcsa <xxxxx@xxxxxxxx.xx.xx>; ^Health: Maree Roberts <xxxxx.xxxxxxx@xxxxxx.xxxx.xx>; Susie Meade <xxxxx.xxxxx@xxxxxxxx.xx.xx>
Cc: xxxxxxxx.xxxx@xxxxxxxx.xxxx.xx; Gill Hall <xxxx.xxxx@xxxxx.xxxx.xx>; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; Pubudu Senanayake <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>; Morag Hatcher <Morag.Hatcher@health.govt.nz>; Sam Tendeter [TSY] <xxx.xxxxxxxx@xxxxxxxx.xxxx.xx>; Patricia Priest <xxxxxxxx.xxxxxx@xxxxxx.xxxx.xx>; Kerryn Fowlie <Kerryn.Fowlie@treasury.govt.nz>; Alastair Cameron [TSY] <xxxxxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; Steven Sue <xxxxxx.xxxxxx@xxx.xxxx.xx>
Subject: RE: Draft Agenda for 12 April COVID-19 Modelling Governance Group

Kia ora koutou
The finalised agenda for Monday is attached (the items are the same), and also included are the papers for each item.

We have literally just received a draft paper from TPM with some modelling results on our border/vaccine questions which we hope to be able to discuss on Monday as well.

From: Christopher Nees [TSY]
Sent: Wednesday, 7 April 2021 4:30 PM
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MSD: Nic Blakeley

<xxx.xxxxxxxxxx@xxx.xxxx.xx>; '^MBIE: Paul Stocks' <xxxx.xxxxxx@xxxx.xxxx.xx>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; 'xxxxx.xxxxxx@xxxxx.xxxx.xx' <xxxxx.xxxxxx@xxxxx.xxxx.xx>; 'xxx.xxxx@xxxxxx.xxxx.xx' < xxx.xxxx@xxxxxx.xxxx.xx>; 'xxxxx@xxxxxxxx.xx.xx' < xxxxx@xxxxxxxx.xx.xx>; ^Health: Maree Roberts <xxxxx.xxxxxxx@xxxxxx.xxxx.xx>; Susie Meade <xxxxx.xxxxx@xxxxxxxx.xx.xx>

Cc: Margaret Galt [TSY] <xxxxxxxx.xxxx@xxxxxxxx.xxxx.xx>; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; Pubudu Senanayake <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>; Morag Hatcher <xxxxx.xxxxxxx@xxxxxx.xxxx.xx>; Sam Tendeter [TSY] <xxx.xxxxxxxx@xxxxxxxx.xxxx.xx>; Patricia Priest <xxxxxxxx.xxxxxx@xxxxxx.xxxx.xx>; Kerryn Fowlie <xxxxxx.xxxxxx@xxxxxxxx.xxxx.xx>; Alastair Cameron [TSY] <xxxxxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^EXT: Steven Sue <xxxxxx.xxxxxx@xxx.xxxx.xx>

Subject: Draft Agenda for 12 April COVID-19 Modelling Governance Group

Kia ora koutou Modelling Governance Group

Ahead of your next meeting on Monday, please see attached a draft agenda which proposes to focus on three substantive items:

1. COVID 19 Modelling strengths and weaknesses
2. Priority policy questions for modelling, and results to date
3. Approach to engaging with the Strategic COVID19 Public Health Advice Group

Please let me know if you have other items you wish to discuss and we will send the papers and final agenda on Friday.

Ngā mihi

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I do not work on Thursdays.

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From: Christopher Nees [TSY]
To: Bryan Chapple [TSY]; ^MSD: Nic Blakeley; ^MBIE: Paul Stocks; Cheryl Barnes [DPMC]; [redacted]
Cc: Margaret Galt [TSY]; Shaan Badenhorst [TSY]; George Whitworth [DPMC]; Pubudu Senanayake; Patricia Priest; Melody&Mark; Gill Hall; ^EXT: Steven Sue; Arati Waldegrave [DPMC]
Subject: RE: Covid-19 Modelling Governance Group
Date: Tuesday, 23 February 2021 2:43:00 PM
Attachments: image001.png
image002.png

Kia ora koutou
Thank you for your time yesterday and the Modelling Governance Group meeting. Below is my record of the key points and actions. Please let me know if you have any amendments and the Steering Group will pick this up the discussion and actions at our meeting next week.

1. **Confirming roles**

The GG endorsed the proposed role and approaches of the Governance and Steering Groups, subject to:

- clarifying where the prioritisation of modelling work should occur –that the GG should set the direction and overall priorities for modelling and the SG would deliver and prioritise within that framework. The TORs will be updated to reflect this.
- membership – consider adding Maree Roberts to the Group to provide a connection into the strategy and policy side

2. **Review of models**

The GG endorsed the proposed parameter review of TPM model, noting:

- It is important to ensure we are comfortable and confident in the underlying approach and assumptions, and we understand how to manage risks to the model (e.g. emergence of new strains)
- We should explore whether international peer review would help with testing the assumptions
- Presentation of the modelling results is also crucial. We need to ensure there is appropriate health expertise involved in review of modelling outputs (as has been discussed in the SG), and 'regularise' the approach to reviewing modelling outputs.
- Challenge for the Steering Group to come back on: is the model set up to address the policy questions we need to answer this year? For example questions about vaccine take up and impact on risk of transmission (which informs approach to elimination strategy).

3. **Use of other models**

- Bryan outlined the Treasury's interest in Wigram's work – including the ability to provide international data and forecasts which will be helpful as vaccines roll out and borders are more open, as well as providing different (complementary) insights to TPM about outbreaks in New Zealand
- The Governance group was comfortable with the Treasury engaging with Wigram, and encouraged both peer review of the underlying model and taking care about if/how conclusions are used in advice

Tsy will explore Wigram's model and keep the GG informed. Report back to GG with an overview of how the methods differ/complement each other, back-casting of performance of models.

- The GG also noted Nick Wilson (et al) previous SEIR model which was used to provide estimates of the probability of elimination. This modelling work could be explored further, if there was interest but would require a new contract and funding.

4. **Work programme**

- The Governance Group wanted to understand:
    - can we pull forward components of the August network modelling programme focussed on MIQ and border management?
    - The relative scale of investment across each four streams and taking care in the way we invest in, and use, social media analysis
    - From the Steering Group, a view about the priority policy questions that we need to address soon where modelling can assist, e.g. role of saliva testing, or testing people one week after leaving MIQ. In other words, what are the next 12 weeks of decisions and how does modelling help with that?
    - Vaccine modelling – challenge is making it relevant to rapidly changing context, advise GG if issues here
- In general the Steering Group was interested to be kept updated on the outputs of the modelling work but didn't expect to engage on it in detail.

5. **Media engagement**

- The GG was comfortable with the proposed approach, but wanted the SG to explore an 'urgent' option where TPM is able to contact Ian T if they need guidance or test comfort on how to address time-sensitive media questions on modelling

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From: Christopher Nees [TSY]
Sent: Friday, 19 February 2021 1:58 PM
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MSD: Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>; ^MBIE: Paul Stocks <xxxx.xxxxxx@xxxx.xxxx.nz>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; xxxxx.xxxxxx@xxxxx.xxxx.xx; Ian.Towx@xxxxxx.xxxx.xx; xxxxx@xxxxxxxx.xx.xx
Cc: Margaret Galt [TSY] <xxxxxxxx.xxxx@xxxxxxxx.xxxx.xx>; Shaan Badenhorst [TSY] <xxxxx.xxxxxxxxxx@xxxxxxxx.xxxx.xx>; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; Pubudu Senanayake <Pubudu.Senanayake@stats.govt.nz>; Patricia Priest <xxxxxxxx.xxxxxx@xxxxxx.xxxx.xx>; Melody&Mark <Melody&xxxx@xxxxxxxx.xxxx.xx>; Jozef Citari [TSY] <Jozef.Citari@treasury.govt.nz>; ^EXT: Steven Sue <xxxxxx.xxxxxx@xxx.xxxx.xx>
Subject: RE: Covid-19 Modelling Governance Group

Kia ora koutou

Please see attached a revised agenda and papers for Monday's meeting on COVID-19 governance.

Ngā mihi

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-----Original Appointment-----
From: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>
Sent: Wednesday, 3 February 2021 11:57 AM
To: Bryan Chapple [TSY]; ^MSD: Nic Blakeley; ^MBIE: Paul Stocks; Cheryl Barnes [DPMC]; xxxxx.xxxxxx@xxxxx.xxxx.xx; xxx.xxxx@xxxxxx.xxxx.xx; xxxxx@xxxxxxxx.xx.xx
Cc: Margaret Galt [TSY]; Christopher Nees [TSY]; George Whitworth [DPMC]; Pubudu Senanayake
Subject: Covid-19 Modelling Governance Group
When: Monday, 22 February 2021 4:15 PM-5:00 PM (UTC+12:00) Auckland, Wellington.
Where: +TSY 3.34 Poutama -16 (EXT) - MS Teams Link enclosed
Importance: High

Agenda:

1. Approval of the Terms of Reference for both this governance group and the Covid-19 Modelling Steering Group. **Drafts are attached**.
2. The contractual agreement and agreement on publicity.*
3. The current work programme.*
4. A discussion on whether there are other modelling priorities.
5. Any other business.

The papers for the items marked * will be supplied later next week. The last two items are discussion points that will not have specific papers.

Microsoft Teams meeting

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Kind Regards
Jozef

Jozef Citari | Te Tai Ōhanga - The Treasury
Executive Assistant to Deputy Secretary for Macroeconomics & Growth – Mr. Bryan Chapple

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From: Christopher Nees [TSY]
To: Bryan Chapple [TSY]
Cc: Jozef Citari [TSY]; Alastair Cameron [TSY]; Shaan Badenhorst [TSY]; Margaret Galt [TSY]
Subject: Proposed agenda for modelling steering group on Monday
Date: Wednesday, 17 February 2021 4:13:00 PM
Attachments: image002.png

Hi Bryan

We have the first modelling Governance Group that you are chairing set up for Monday afternoon for 45mins. Invited are essentially the group that Tim pulled together last year, although they only met a couple of times: Paul S, Juliet Gerrard, Ian Town, Cheryl B, Nic B, Vince G (StatsNZ).

Below is a suggested agenda which we'd be grateful for your feedback on. I've also put it to the Steering Group and there may be a few tweaks depending on their feedback (M&M chair the Steering Group, includes Shaun H, and has met twice so far)

1. **Confirming the role of this group**

Purpose: agree to role, endorse role of steering group and agree on frequency of meetings

Proposed TOR for the GG are here, Terms of Reference for COVID-19 Modelling Governance Group (Treasury:4418182v1) Add to worklist but the elevator pitch is this group exists to:

- Provide direction and oversight of the modelling programme to ensure it contributes to the COVID-19 response
- Prioritise what epidemiological, economic and social questions that may be answered through modelling work
- Remove barriers to manage resource needs funding, data, capability in respective agency
- Facilitate dissemination, socialisation and champion modelling outputs

2. **Modelling quality and approaches**

Purpose:

a) to seek GG endorsement of a 'parameter review' of the TPM model. Context here is MoH (Ian T), AOG and to some extent us have concerns about some of the underlying assumptions in the TPM model. E.g. that they under-estimate the ability of our TTI system to respond to an outbreak. MoH are keen to progress a review of the key assumptions and parameters which we support.

b) for us to raise interest in looking at other modelling approaches (e.g. that of Wigram) and test reactions. The purpose being to broaden out the modelling community and understanding of different approaches. This has been a bit fraught to date because of concerns about non-public health experts getting into this work (including TPM!), so getting some comfort from the group that we should be opening up would be helpful.

3. **TPM work programme and funding**

Purpose: ensure the GG is aware of the revised programme, signal any areas where they'd like to specifically engage on the results of the work and if there are wider modelling issues or questions they are interested in

Context: TPM have developed a revised work programme reflecting feedback from the GG last year. Their contract is about to be extended for six months, with longer term funding arrangements subject to MBIE budget bids.

4. Managing TPMs media engagement

Purpose: to endorse principles for media engagement on TPMs work.

Context: this will be a short item but think it's worth raising as officials have had concerns last year about the extent to which TPM talks about modelling issues in public, especially before their outputs have been through peer review and Ministers are across them. MoH would prefer he doesn't comment at all. Juliet G is a key contact of Shaun H and has helped to manage the balance last year and Tim had discussed with her. He apparently also clears some of his media engagement with her. We've worked up some relatively pragmatic principles that balance between MoH and TPM.

Ngā mihi

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From:	George Whitworth [DPMC]
To:	Bryan Chapple [TSY]; ^MBIE: Paul Stocks; pmcsa; Vince Galvin; ^MSD: Nic Blakeley; Ian Town
Cc:	Mary van Andel; Christopher Nees [TSY]; Patricia Priest; Arati Waldegrave [DPMC]; Melody&Mark
Subject:	FW: Vaccination and testing of the border workforce - impacts on surveillance. TPM modelling report with cover note.
Date:	Monday, 15 February 2021 6:43:28 PM
Attachments:	image001.png image002.png image003.png image004.png vaccination and border workers cover note 15022021.docx vaccination and testing border workforce.pdf image005.png

[IN-CONFIDENCE]

Good evening all,

I understand from Chris that you are to meet next week to discuss a collective future role as the governance group for the COVID-19 related modelling work programme.

As part of this role, we (typically referring to Trish, Mary, Chris and myself, with support of others where required) would expect to keep you appraised of notable modelling outputs as we receive them, alongside Health and DPMC colleagues included in Mary's previous email. In turn, we'd expect this to influence decisions around the nature of work we seek to commission through our academic and agency partners.

This email pertains to some recent and pre-peer-review material which the TPM branching process modellers shared with us and some health colleagues last week. We are sharing now as it pertains to the imminent commencement of the Tier 1 immunisations of border workforces.

Thanks
George

George Whitworth
Special Advisor, COVID-19 Group
Department of the Prime Minister and Cabinet

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From: Mary van Andel <xxxx.xxxxxxxx@xxx.xxxx.xx>
Sent: Monday, 15 February 2021 2:53 pm
To: Arati Waldegrave [DPMC] <xxxxx.xxxxxxxxxx@xxxx.xxxx.xx>; Ian Town <xxx.xxxx@xxxxxx.xxxx.xx>; Gill Hall <xxxx.xxxx@xxxxxx.xxxx.xx>; Antony.xxxxx@xxxxxx.xxxx.xx; Ashley Bloomfield <xxxxxx.xxxxxxxxxx@xxxxxx.xxxx.xx>; Stephen Harris <Stephen.Hxxxxx@xxxxxx.xxxx.xx>; Ian Town <xxx.xxxx@xxxxxx.xxxx.xx>; Caroline McElnay <Caroline.McElnay@health.govt.nz>; Sue Gordon <xxx.xxxxxx@xxxxxx.xxxx.xx>; Therese Egan <xxxxxxx.xxxx@xxxxxx.xxxx.xx>; Melody&Mark <Melody&xxxx@xxxxxxxx.xxxx.xx>
Cc: Patricia Priest <xxxxxxxx.xxxxxx@xxxxxx.xxxx.xx>; ^EXT: Talosaga Talosaga <xxxxxxxx.xxxxxxxx@xxxxxx.xxxx.xx>; George Whitworth [DPMC] <George.Whitxxxxx@xxxx.xxxx.xx>; Deborah Read <xxxxxxx.xxxx@xxxxxx.xxxx.xx>; Chris Peck <Chris.Peck@health.govt.nz>; Michael Bunce <xxxxxxx.xxxxx@xxxxxx.xxxx.xx>; Dan Bernal <Daniel.Bernal@health.govt.nz>

Subject: Vaccination and testing of the border workforce - impacts on surveillance. TPM modelling report with cover note.

Kia ora koutou

At the end of last week, TPM provided a draft modelling report describing the effect of vaccination on surveillance at the border. The paper and a cover note with interpretation and recommendations are attached here for your attention. This interpretation has been worked on by myself, Trish and George. We are working in a coordinating and interpreting capacity in this instance and hope you find it useful.

In short, the results of this modelling highlight the need to methodically work through the effect that vaccination could have on each of the pillars of the Elimination Strategy in the next short time. This is illustrated in this case by focussing on the effect that different levels of transmissibility following vaccination might have on community incursions from MIQs and the requirements for border worker testing.

Please don't hesitate to get in touch if you would like to discuss further

All the best
Mary

Mary van Andel, BVSc, MVS (Cons Med), MVS (Epidemiology), MANZCVS (Epidemiology), PhD (Epidemiology) | Principal Advisor Epidemiology | Biosecurity New Zealand
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On 11 February, Te Pūnaha Matatini shared a pre-review draft paper titled “Vaccination and testing of the New Zealand border workforce for COVID-19 and risk of community outbreaks” in the context of a meeting on vaccines strategy modelling work with officials from the Ministry of Health, DPMC, Pharmac and ESR. We are providing sight of this output now, despite its draft status, on account of the near-term implications it raises in relation to our immunisation and elimination strategies and their ongoing review.

Briefly, the paper highlights the risk to the elimination strategy associated with vaccinating the border workforce. This risk assumes that vaccination may suppress symptoms of COVID-19 in frontline workers but not entirely remove the possibility of transmission of SARS-CoV2 should infection occur. Although there is uncertainty around this assumption in the case of SARS-CoV2, this is a reasonable concern and aligned with infectious disease management principles.

Symptom presentation has been an important feature of our Elimination Strategy: of 6 infection events in the border workforce, only 2 have been detected by routine testing. If these individuals had not opted to present themselves for testing because of their symptoms, they would not have been detected as active cases until their next routine test. This would have resulted in more time in which these cases could have interacted with others in their communities, potentially resulting in additional cases prior to detection.

The degree of transmission reduction of SARS-CoV2 achieved in vaccinated populations is not yet known. Model outputs are very sensitive to changes in this parameter.

- The draft paper highlights that in a pessimistic scenario (with complete suppression of symptoms but no reduction in transmission) the aggregate risk of incursion in the community increases relative to the status quo. This pessimistic scenario is in our estimation unlikely.
- Less pessimistic assumptions might not lead to an overall increase in transmission risk to the community but may have significant implications for the way in which this transmission risk manifests and therefore the optimal surveillance strategy for detecting new cases.

This result highlights the need to methodically work through the implications of vaccination for the pillars of the Elimination Strategy. There are a number of similar and related questions which will become urgent in the time period between the start of vaccination and the time when sufficient individuals in the population are vaccinated to provide the conditions that prevent uncontrolled disease transmission.

Te Pūnaha Matatini
Data ▪ Knowledge ▪ Insight

Note: This paper has not yet undergone formal peer review

Supplied in confidence: not for general release

Vaccination and testing of the New Zealand border workforce for COVID-19 and risk of community outbreaks

11 February 2021

Michael J. Plank[1,4], Alex James[1,4], Rachelle N. Binny[2,4], Shaun C. Hendy[3,4], Audrey Lustig[2,4], Kannan Ridings[3,4]

1. School of Mathematics and Statistics University of Canterbury, New Zealand.
2. Manaaki Whenua, Lincoln, New Zealand.
3. Department of Physics, University of Auckland, New Zealand.
4. Te Pūnaha Matatini: the Centre for Complex Systems and Networks, New Zealand.

Executive Summary

- Frontline border workers are a priority group for early vaccination against COVID-19 once vaccine supplies arrive in New Zealand.
- The effectiveness of COVID-19 vaccines in preventing transmission is currently unknown.
- There is a danger that vaccination could suppress symptoms of COVID-19 in frontline workers but not prevent transmission.
- In a pessimistic vaccine scenario, this could approximately double the risk of a large community outbreak.
- This risk can be mitigated by increasing the frequency of routine testing of frontline workers.

Introduction

Since October 2020, the large majority of COVID-19 cases in New Zealand have been detected in international arrivals and contained within managed isolation and quarantine (MIQ) facilities at the border. In the period from October 2020 to early February 2021, there have been at least 9 border breaches, resulting in an active case of COVID-19 entering the community. Of these 9 breaches, 5 have been caused by a MIQ worker being infected by contact with a case, and 2 have been associated with transmission of COVID-19 between recent arrivals within MIQ.

While there is no community transmission of COVID-19 in New Zealand, frontline border workers are the group with the highest risk of being infected with COVID-19. This group is therefore being prioritised for vaccination . Approved vaccines are proven to be effective in reducing the incidence of symptomatic disease. Vaccination will reduce the health risk for frontline workers. However, it remains unknown how effective vaccines will be in reducing infection and transmission of COVID-19. If the vaccine is effective in preventing frontline workers from becoming infected or transmitting COVID-19, vaccination of frontline workers will provide an additional buffer that will help protect the wider community against border reincursions. However, if the vaccine does not prevent infection or transmission, there is a danger that vaccinating frontline workers could increase the risk of community outbreaks, by making the initial infection in a frontline worker harder to detect. This danger could be mitigated by increased testing of frontline workers.

In this report, we use a model for transmission and testing of COVID-19 to investigate the risk of a community outbreak under various vaccination and testing scenarios.

Methods

We use the COVID-19 community transmission model of James et al. (2020), seeded with an infected frontline worker. All border workers undergo regular scheduled nasopharyngeal PCR tests with symptom checks. We assume that the symptom checks by health professionals help to provide a very low probability that cases are missed by testing after symptom onset. For example, symptomatic individuals may be retested and/or classified as probable cases in the absence of a positive PCR test result. We assume that border workers may also receive an additional test triggered by symptom onset, with an average delay of 2 days from symptom onset to test result. We assume there is no routine testing in the general population (i.e. non-border workers) and a longer average delay of 6 days from symptom onset to test result.

We assume that 33% of COVID-19 infections are subclinical and these have 50% of the transmission rate of clinical cases. We also assume that nasopharyngeal PCR tests in subclinical individuals have a lower sensitivity, 65% of the sensitivity for clinical cases and declining over time after symptom onset (Kurcirka et al., 2020).

We investigate how vaccinating the border workforce affects the risk of a community outbreak under various vaccine effectiveness and testing scenarios. Approved vaccines are known to be effective in preventing symptomatic disease caused by SARS-CoV-2. However, it is still uncertain how effective they are in reducing infection or transmission of the virus. If a vaccine suppresses symptoms of COVID-19 in frontline border workers but does not prevent them from transmitting the virus, there is a danger this could increase the risk of community outbreaks by making it harder to detect the virus in the seed cases, and therefore more likely that the outbreak could spread into the community before being detected.

We first investigate a pessimistic scenario in which the vaccine is 100% effective in preventing symptoms of COVID-19 but does not reduce infection or transmission of the virus at all. This represents a worst-case scenario from the point of view of the likelihood of a community outbreak. A more realistic scenario is that the vaccine is partially effective in preventing transmission. To model this, we assume that the virus is 100% effective in preventing symptoms and 50% effective in reducing transmission (i.e. the reproduction number for vaccinated individuals is 50% of that in unvaccinated individuals). For simplicity, we assume all frontline border workers are vaccinated and the remainder of the population is unvaccinated.

Prevention of symptomatic disease in vaccinated border workers has two effects on the testing model. Firstly, it means that border workers only get routine scheduled tests (e.g. weekly tests) and do not get additional symptom-triggered tests that they may get if they were unvaccinated. Secondly, it means that cases cannot be flagged for repeat testing or diagnosed or probable case as a result of symptom checks. This increases the likelihood of an infected individual being missed by a PCR test. These are conservative assumptions that assume the vaccine is completely effective in preventing symptomatic disease.

For each vaccine scenario, we examine the risk of community outbreaks under different routine testing frequencies for border workers. We calculate the proportion of simulations, each seeded with a single infected border worker, in which the outbreak is (i) never detected, (ii) first detected in the seed case (generation 1 detection), or (iii) first detected in a secondary case or later (generation 2+ detection). We also calculate the size of the outbreak (total number of people infected) at the time it is first detected.

Results

Table 1 shows the probability that a single infected frontline worker leads to an outbreak that dies out without being detected, is detected in generation 1, or is detected in generation 2 or later. For outbreaks detected in generation 1 or in generation 2+, Table 1 also shows the median number of infected individuals at the time of detection (referred to as outbreak size).

Without vaccination and with scheduled weekly testing of frontline workers (representing the current situation in early February 2021), 5.9% of simulations result in the outbreak dying out without being detected, 88.2% of simulations result in an outbreak detected at generation 1 and 5.9% result in an outbreak detected at generation 2+. For generation 1 detections, the median outbreak size is 1 (i.e. there are no infections apart from the frontline worker seed case) and the interquartile range 1 – 4). For generation 2+ detections, the median outbreak size is 16 (interquartile range 6 –36.5). Consistent with our previous modelling work, this shows that if a case is detected outside the frontline worker group, it is likely that there are much larger number of people already infected.

With a vaccine that does not reduce transmission and with scheduled weekly testing, 8.9% of simulations result in the outbreak dying out without being detected, 78.3% of simulations result in an outbreak detected at generation 1 and 12.8% result in an outbreak detected at generation 2+. For generation 1 detections, the median outbreak size is 2 (interquartile range 1 – 6) and for generation 2+ detections, the median outbreak size is 23.5 (interquartile range 10 – 41.5). This shows that the frequency of generation 2+ detections is approximately double that in the no-vaccination scenario,

and the outbreak size for generation 2+ detections tends to be larger than in the no-vaccination scenario.

With a vaccine that does not reduce transmission and with scheduled testing every 4 days, 2.5% of simulations result in the outbreak dying out without being detected, 91.4% of simulations result in an outbreak detected at generation 1 and 6.1% result in an outbreak detected at generation 2+. For generation 1 detections, the median outbreak size is 2 (interquartile range 1 – 5) and for generation 2+ detections, the median outbreak size is 16.5 (interquartile range 8 – 38). This shows that the risk of community outbreaks due to vaccine-induced symptom suppression in frontline workers can be mitigated by increasing the testing frequency from 7 days to 4 days.

The results described above represent a pessimistic scenario about the characteristic of the vaccine: that it is 100% effective in suppressing symptoms and 0% effective in reducing transmission. It is likely that a vaccine that prevents symptomatic disease will provide at least some reduction in transmission, although the size of the reduction is unknown at this time. Results for a more optimistic scenario where the vaccine reduces transmission by 50% show that the risk of community outbreaks is not as great as when the vaccine does not reduce transmission. For example, with a 50% effective vaccine and weekly testing, the probability of a generation 2+ detection is 9.0%. Increasing the testing frequency from 7 days to 4 days more than compensates for this increased risk, reducing the probability of a generation 2+ detection to 3.6%, which is lower than the status quo estimate of 5.9%.

Scenario	**Test freq.**	**Detection type**			**Outbreak size gen. 1**	**Outbreak size gen. 2+**
		Undet.	Gen. 1	Gen. 2+		
No vaccine	14 days	0.111	0.791	0.098	2.0 [1.0 4.0]	17.0 [7.0 38.0]
No vaccine	7 days	0.059	0.882	0.059	1.0 [1.0 4.0]	16.0 [6.0 36.5]
No vaccine	4 days	0.023	0.942	0.034	1.0 [1.0 4.0]	18.0 [7.0 38.0]
No vaccine	2 days	0.003	0.985	0.012	1.0 [1.0 4.0]	13.5 [5.0 34.0]
Vaccine 0% eff	14 days	0.208	0.541	0.252	2.0 [1.0 6.0]	24.0 [11.0 46.0]
Vaccine 0% eff	7 days	0.089	0.783	0.128	2.0 [1.0 6.0]	23.5 [10.0 41.5]
Vaccine 0% eff	4 days	0.025	0.914	0.061	2.0 [1.0 5.0]	16.5 [8.0 38.0]
Vaccine 0% eff	2 days	0.002	0.981	0.016	2.0 [1.0 5.0]	11.0 [5.0 26.0]
Vaccine 50% eff	14 days	0.262	0.556	0.182	1.0 [1.0 3.0]	21.0 [8.0 48.0]
Vaccine 50% eff	7 days	0.116	0.794	0.090	1.0 [1.0 3.0]	17.0 [7.0 37.0]
Vaccine 50% eff	4 days	0.035	0.928	0.036	1.0 [1.0 3.0]	11.0 [5.0 25.0]
Vaccine 50% eff	2 days	0.003	0.985	0.012	1.0 [1.0 3.0]	8.0 [4.3 17.8]

Table 1. Model results for 3 vaccination scenarios (no vaccination of frontline workers, a vaccine that is 0% effective at preventing transmission, and a vaccine that is 50% effective at preventing transmission) different frequencies of routine testing of frontline workers. The "Detection type" columns show the proportion of model simulations that result in: an outbreak that dies out without being detected (Undet.); an outbreak that is first detected in the seed case (Gen. 1); and an outbreak that is first detected in a secondary case or later (Gen. 2+). The "Outbreak size" columns show the median [interquartile range] number of infected individuals at the time the first case is detected. Results are from 5000 independent simulations of the model, each initialised with a single seed case in a frontline worker.

Discussion

We used a stochastic branching process of COVID-19 transmission and testing to assess the risk of community outbreaks under various frontline worker vaccination and testing scenarios. Under a pessimistic scenario of a vaccine that suppresses symptoms but does not prevent transmission, vaccination of frontline workers could approximately double the risk of a large community outbreak. This risk can be mitigated by increasing the frequency of routine testing of frontline workers from once per week to once every 4 days. Under a more optimistic scenario of a vaccine that is partially effective in preventing transmission, the increase in risk due to vaccination of frontline workers is smaller.

For simplicity, we assumed that all tests have the same time-dependent sensitivity curve (Kucrika et al., 2020), representing a gold-standard PCR nasopharyngeal swab test. If tests with a lower sensitivity are used to complement the weekly nasopharygenal swab test, these may need to be done more frequently (e.g. daily saliva testing) – see James et al. "Combining nasopharyngeal swab and non-invasive tests for COVID-19 surveillance in frontline workers" for more details.

Acknowledgements

The authors acknowledge the support of Stats NZ, ESR, and the Ministry of Health in supplying data in support of this work. This work was funded by the New Zealand Ministry of Business, Innovation and Employment and Te Pūnaha Matatini, Centre of Research Excellence in Complex Systems.

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Kucirka LM, Lauer SA, Laeyendecker O, Boon D, Lessler J. (2020) Variation in false-negative rate of reverse transcriptase polymerase chain reaction–based SARS-CoV-2 tests by time since exposure. Annals of Internal Medicine 173:262-7.

From: Christopher Nees [TSY]
To: Bryan Chapple [TSY]
Cc: Tim Ng [TSY]; Geraldine Treacher [TSY]; Melody&Mark; Ben Temple [TSY]; Bettina Schaer [TSY]
Subject: overview of what the modelling governance role looks like
Date: Tuesday, 15 December 2020 2:06:00 PM
Attachments: image003.png

Kia ora Bryan

We spoke briefly the other day about you picking up Tim's role in governing the COVID-related modelling across govt and I said I'd send you a summary of what's involved and resourcing etc. Here's my take on it – Tim you may wish to add/correct things!

Our objectives for the role:

- started with trying to join up all the cross agency threads and demand for TPM modelling, to make their job easier but also to try and prioritise and engage in their work so we understand what's behind the numbers that go to Ministers
- more recently we've been aiming to bring the economic analysis and modelling alongside the health modelling so that they are not seen as in competition with each other. There's still a lot we can do here but we started with Sense Partners presenting their CGE work to the health modellers.
- Relatedly we are keen to broaden the diversity of models used in this area and have been engaging with Wigram about their approach and where it might add value.

There are three key parts to the role:

- A Dep Sec Governance Group that Tim reinstated to meet on an ad hoc basis. Most recently they met to discuss the TPM proposed work programme and we used their feedback to provide a collective view back to MBIE about what work should recvive further funding. Their TOR are here: Terms of Reference for COVID-19 Modelling Governance Group (Treasury:4347848v1) Add to worklist
- A weekly meeting with TPM (Shaun), AOG (George), MoH and Tsy where we run through the current work, discuss/feedback on papers and deal with other issues (e.g. Christmas cover, their funding arrangements(
- A roughly six weekly modelling workshop series, where the results of a range of work are presented and discussed around the modelling community (both health and economic).

The resourcing involved is:

- Tim in a chairing role across all three areas above
- Ben T around 0.4-0.5FTE being across the modelling work, coordinating comments and feedback and engaging on the detail of their modelling outputs. With Ben moving on we have done some handover to Margaret G but she is relatively fresh in terms of her background on the work so far.
- Luke Symes from A&I around 0.2-0.3 FTE as a modelling expert and engaging on the detail of the outputs. I'm discussing with Patrick whether we can keep access to him in 2021.
- Me around 0.2 in a loose coordination role – e.g. on the funding side

We've also had assistance from Bettina in terms of Wigram's work and there are others in the team who engage in the modelling outputs.

Let us know if lines up with what you and in mind and if it would be useful to discuss the

approach and objectives.

A suggested way forward would be to reconvene the Governance Group in the New Year to revisit the modelling priorities and discuss how to broaden the diversity of models we use in the advice. This particularly requires buy-in from MoH who we have only recently managed to include in our weekly sessions with Shaun H.

Ngā mihi

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From: Christopher Nees [TSY]
To: Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; xxxxx.xxxxxx@xxxxx.xxxx.xx; Ian Town; pmcsa; ^EXT: Talosaga Talosaga; x.xxxxxxx@xxxxxxxx.xx.xx
Cc: George Whitworth [DPMC]; xxxxxxxx.xxxxxxxx@xxx.xxxx.xx ; Gill Hall; Pubudu Senanayake; Patricia Priest; xx@xxxxx.xx.xx ; Caleb Morrall [TSY]; Harry Nicholls [TSY]
Subject: Agenda and papers for Friday"s Covid-19 Modelling Governance Group
Date: Wednesday, 1 September 2021 11:22:10 AM
Attachments: 4511535_4482665_Agenda - COVID Modelling Governance Group meeting 3 September.DOCX
image001.png
4501433_Interpreting the border testing and quarantine paper.PDF
v0.7 Vaccination and Border Testing.docx
v0.7 Additional Outbreak Results.docx
4499477_Modelling approaches to managing COVID (DRAFT).DOCX
image002.png

Kia ora koutou
Please find attached an agenda and papers for Friday.

Ngā mihi

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From: Christopher Nees [TSY]
Sent: Tuesday, 31 August 2021 2:01 PM
To: Bryan Chapple [TSY] <x@xxx; ^MBIE: Paul Stocks <x@xxx; ^MSD: Nic Blakeley <x@xx.nz>; Cheryl Barnes [DPMC] <x@xxx; x@xx.Ian Town <x@xxx; pmcsa <x@xxx; ^EXT: Talosaga Talosaga <x@xxx; x@xx
Cc: George Whitworth [DPMC] <x@xxx; x@xx.Gill Hall <x@xxx; x@xx.Patricia Priest <Patricia.Priest@health.govt.nz>; x@xx.Caleb Morrall [TSY] <x@xxx; Harry Nicholls [TSY] <x@xxx
Subject: RE: Covid-19 Modelling Governance Group

Kia ora koutou

Our proposed agenda for this Friday is:

1. An overview of the modelling on the current resurgence. This is to give you a picture of the latest work and understand our modelling cycle with TPM.
2. Latest draft results on the 'border reopening scenarios' paper. We introduced this work at the last meeting and have an updated but not final draft from TPM
3. Proposed modelling work on options for managing COVID-19 as vaccination rates increase. This work is similar to what has been recently undertaken in Australia and aims to look at what bundles of public health restrictions are sufficient to control resurgences when vaccination rates are high, how long they are needed for, and their economic impacts.

Please let me know if you have further items you'd like to cover.

Ngā mihi

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-----Original Appointment-----
From: Steph Tims [TSY] <x@xxx> **On Behalf Of** Bryan Chapple [TSY]
Sent: Wednesday, 18 August 2021 5:05 PM
To: Bryan Chapple [TSY]; Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; x@xxx; Ian Town; pmcsa; ^EXT: Talosaga Talosaga; x@xxx; Christopher Nees [TSY]; Harry Nicholls [TSY]; Caleb Morrall [TSY]
Cc: George Whitworth [DPMC]; x@xxx; Gill Hall; x@xxx; Patricia Priest; @xxx
Subject: Covid-19 Modelling Governance Group
When: Friday, 3 September 2021 12:45 PM-1:30 PM (UTC+12:00) Auckland, Wellington.
Where: (MS Teams); +TSY 3.30 Purapura -46 -MS Teams (EXT)

Hi all –
Rescheduling this from 20/8 to 3/9 – apologies for hijacking the lunch break!
Agenda and papers will be circulated in advance.

Cheers. Steph

Steph Tims (she/her) | **Te Tai Ôhanga – The Treasury**
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Agenda: COVID-19 Modelling Governance Group 3 September 2021

Chair: Bryan Chapple, Deputy Secretary, Macroeconomics and Growth, **The Treasury**

Members: **DPMC**: Cheryl Barnes, **MOH**: Ian Town, Talo Talosaga **MBIE:** Paul Stocks, **StatsNZ:** Vince Galvin **MSD:** Nic Blakeley, **PMCSA**: Juliet Gerrard.

1. **Welcome and apologies** (apologies from Nic)

2. **General updates/context (all)**

   Purpose: To share information on recent developments. Possible items include:

   - Recent discussion with Sir David Skegg on modelling work (George)

3. **An overview of the modelling on the current resurgence (George)**

   Purpose: To give you a picture of the latest modelling of the current resurgence and understand our modelling cycle with TPM.

4. **Update and summary of TPM's border testing and quarantine paper (Chris)**

   Purpose: to discuss the key results of TPM's modelling work on border reopening.

   Papers: Interpreting the border testing and quarantine paper (summary from Officials), Vaccination and Border Testing (paper from TPM), Additional Outbreak Results (paper from TPM)

   Context: Since your last meeting TPM has progressed this paper that looks at the risks from different forms of border reopening. The paper is undergoing technical and public health review before briefing Ministers and publication (timing TBC).

5. **Modelling to support management of COVID-19 at high levels of vaccination (Chris)**

   Purpose: To share and seek feedback on proposed modelling to understand what degree of public health restrictions would manage COVID when community vaccination is high

   Papers: Modelling approaches to managing COVID-19

   Context: We are commissioning modelling from TPM to help understand what 'bundles' of public health restrictions would be sufficient to manage COVID outbreaks once community vaccination is at high levels. This is similar to recent work in Australia that found permanent 'baseline' restrictions (limiting venue capacity, square metre rules) were the most effective way to manage COVID so as to not exceed the limits of the contact tracing system.

   Importantly such modelling needs to be informed by assessments of 'real world' re-openings, for example in Singapore. This work is also being progressed by DPMC.

6. **Any other business (Bryan)**

   Purpose: To discuss any outstanding matters.

Interpreting the Vaccination and Border Testing paper

For: Modelling Governance Group, 3 September

From: Modelling Steering Group

Why was this modelling commissioned?

- The purpose of this modelling is to quantify the relative risk of community outbreaks using different bundles of mitigation measure for international travellers arriving into New Zealand
- The model assesses the "transmission potential" of a traveller with different border/arrival interventions, the risk of onward transmission into the community from a traveller, and the probability of an infected traveller starting a large outbreak.
- The model is therefore useful to inform policy decisions about options for how the border could be opened in different ways, as the vaccine rollout continues.

What are the key results?

The paper sets out the impact of using many different combinations of pre-departure and arrival measures to manage risk. For simplicity the table below focusses on results that relate to:

- reopening only to vaccinated travellers
- reopening only where community vaccination reaches 80%
- reopening scenarios using three 'bundles of interventions': daily testing, 5 day self-isolation, and 7 day MIQ

The results are best interpreted as providing a sense of the relative risk of different options, rather than precise estimates that predict outcomes.

	Reduction in transmission potential (relative to non-vaccinated traveller with no pre-departure testing)	Probability of onward transmission from an infected traveller with 80% community vaccine coverage	Probability of a large outbreak from an infected traveller with 80% vaccine coverage	Number of travellers per large* outbreak with 80% vaccine coverage
Vaccinated traveller	50%	15%	8%	13
Daily LFT tests for 5 days	77%	8%	4%	25
5 day self isolation with daily rapid tests	90%	5%	2%	50-54
7 day MIQ with PCR testing	99.8%	0.1%	0.1%	1000+

What are the notable results?

- The model shows there is no point at which vaccination rates mean that borders can open without creating community outbreaks (noting that the maximum modelled vaccination coverage is 90% of 16+ year olds).

- High levels of community vaccination make a material reduction to the risks from international arrivals. For example, with 60% vaccination rates, the risk of a large outbreak is 40-50% higher than if community vaccine coverage is 80%.
- Vaccination status has the largest single effect in reducing transmission potential of a traveller, followed by the use of post-arrival restrictions. Pre-departure tests have a small effect.
- Rapid antigen tests look like a particularly useful intervention to use to test frequently and quickly, supplemented with some PCR testing. (noting there is large variability around the type and effectiveness of these tests).
- While the model assumes vaccinated infected travellers are 50% as "risky" as non-vaccinated travellers, they are also less likely to be infected in the first place. This means they are even less "risky" than this analysis would otherwise suggest.

What are some of the limitations/key points of interpretation?

- The model is not set up to consider differences in traveller risk which we know will vary according to where they have spent the previous 14 days before arriving in NZ. This suggests the results may be pessimistic if considering arrivals from low-risk countries, but optimistic if the arrivals are from high-risk countries. More permissive entry requirements may be appropriate for the former, but the more restrictive measures would be necessary for the latter.

- Travel volumes also matter. If restrictions are implemented that reduce the risk 10 fold, but there is a 100 fold increase in travellers (or increase in travellers from high risk countries such that the number of infected travellers increases 100 fold), then there will be a 10 fold increase in risk.

- The model assumes self-isolation is 60% effective in reducing transmission for asymptomatic travellers and80% effective for symptomatic travellers. The actual rate would reduce if there is poor compliance but improve if there were policies such as requiring household contacts to be vaccinated or with mechanisms to 'enforce' self isolation.

- The model assumes contact tracing is the only intervention used to manage instances of community transmission and that there are no 'baseline' public health measures in place (e.g. mandated mask wearing, permanent limits on venue capacity etc). This may mean that the risks of community outbreaks are overstated because public health restrictions are likely to be used in response to case identification.

- The model also assumes a relatively low rate of community testing (12% of symptomatic individuals), reflecting experience, but interventions to increase this rate would mean cases are detected more quickly and potentially avoid large outbreaks.

- The model does not show the health impacts of these outbreaks, which will become smaller (but never zero) with higher levels of vaccination. In other words, understanding health outcomes rather than case numbers will become more important when vaccination levels are high.

NOT YET PEER REVIEWED

Effect of vaccination and border testing and quarantine requirements on the risk of COVID-19 in New Zealand: a modelling study

Nicholas Steyn[1,3], Michael Plank[2,3], Shaun Hendy[1,3], …

1. Department of Physics, University of Auckland, New Zealand.
2. School of Mathematics and Statistics, University of Canterbury, New Zealand.
3. Te Pūnaha Matatini, Centre of Research Excellence in Complex Systems, New Zealand.

Abstract

We couple a simple model of quarantine and testing strategies for international travellers with a model for transmission of SARS-CoV-2 in a partly vaccinated population. This is used to consider the risk reduction achieved from implementing various non-pharmaceutical interventions at the border as well as the implications for onward spread in the community. Key outputs include the reduction in transmission potential from various strategies, the probability that an arrival triggers a “serious” outbreak, and the expected frequency of such outbreaks. Various definitions of “serious” are considered.

NOT YET PEER REVIEWED

Introduction

Since April 2020, New Zealand has pursued a COVID-19 elimination strategy and, through a combination of strict border controls and snap lockdowns when needed, has seen very limited community transmission since the last significant outbreak in August 2020 (REF Baker et al). As a result New Zealand has negligible infection-acquired immunity to COVID-19 (REF antibody study). New Zealand's national vaccination programme began in February 2021 and is using the Pfizer/BioNTech mRNA vaccine. As of mid-August 2021, around 16% of the population are fully vaccinated and an additional 10% have received their first dose [1]. The government aims to offer the vaccine to everyone who is eligible by the end of 2021

During 2021, the Delta variant of SARS-CoV-2 has displaced other variants and become dominant in many countries, including India, the UK and USA – countries with which New Zealand has close travel links. Because of the increased transmissibility of the Delta variant, it is unlikely that countries will be able to reach complete population immunity (i.e. a reproduction number that less than 1 in the absence of any other interventions) via vaccination alone [2]. Other public health measures will be needed to control the virus, although reliance on these will reduce as vaccine coverage increases. These measures may consist of a mixture of border controls designed to reduce the risk of cases being seeded into the population, and community measures designed to enhance surveillance and reduce the potential for transmission.

With current levels of vaccine coverage and given the increased transmissibility of the Delta variant, New Zealand's current requirement of 14 days in government-managed isolation for international arrivals is still needed to prevent the virus entering the community. At present, any border-related cases would have the potential to cause rapidly growing community outbreaks that would be impossible to control without lockdown measures [2]. However, once vaccination coverage is sufficiently high, it will be possible to gradually relax border controls in conjunction with ongoing community public health measures. To do this safely, it will be important to quantify the relative risk of community outbreaks under different sets of mitigation measures for international travellers arriving to New Zealand. These may include

different combinations of government-managed isolation and quarantine (MIQ), self-isolation at home, and pre-departure and post-arrival testing requirements. Different sets of requirements could be applied to travellers depending on their risk profile, for example more stringent restrictions for people travelling from countries with high infection rates.

New Zealand has primarily used RT-PCR tests for SARS-CoV-2 testing throughout the pandemic, sometimes known as the gold standard test because of its high sensitivity. Around the world, countries are increasingly complementing PCR testing with rapid antigen tests, also known as lateral flow tests. These have lower sensitivity that PCR tests, particularly in the early and late stages of the infectious period [3]. However, they have the advantage that they return results very quickly (typically within 30 minutes), they are cheap, and they do not require lab processing. This means they can be used to test large numbers of people at high frequency (e.g. daily) without stretching lab capacity and with fast turnaround of results.

Travel volume is a key determinant of the risk posed by international travel. As a consequence of limited MIQ capacity and citizenship or residence requirements for entry, the volume of international arrivals to New Zealand has been approximately 2% of pre-pandemic levels (with the exception of arrivals from Australia during limited periods of quarantine-free travel). It is important to factor this into risk evaluations because if, for example, a given mitigation provides a 10-fold reduction in the risk per arrival, this will be offset if there is a simultaneous 10-fold increase in travel volume.

In this paper, we use a stochastic model of SARS-CoV-2 transmission and testing to compare the relative reduction in transmission potential from infected travellers under various mitigations and at different levels of vaccine coverage in the resident population. This paper is a policy-oriented application of the model developed by [2] to investigate the potential impact of COVID-19 at different stages in New Zealand's vaccination programme.

The model allows for different effectiveness of isolation under different circumstances, for example MIQ versus self-isolation at home during asymptomatic, pre-symptomatic, symptomatic or confirmed stage of infection. We compare different testing requirements, such as daily LFTs or less frequent PCR tests, allowing for the different sensitivity of these

tests. The model also includes individual heterogeneity in transmission rates and the probability of returning a positive result if tested.

We use the model to simulate community outbreaks seeded by international arrivals and calculate the probability that such an outbreak meets various pre-defined criteria. The aim is not to identify vaccination targets at which borders can be completely reopened, but rather to support strategies for safe relaxation of travel restrictions by comparing the risk reduction from various policy options.

The modelling approach is similar to that of Quilty et al, who estimated the reduction in transmission potential from a range of traveller interventions. The model of Quilty et al modelled individual heterogeneity in viral load trajectories and effectively assumed a one-to-one mapping between viral load, transmission rate and probability of testing positive. We found it difficult to reconcile this with the fact that there is significant pre-symptomatic transmission of SARS-CoV-2 and that the likelihood of individuals testing positive in the pre-symptomatic stage appears to be significantly lower than after symptom onset. We therefore take a simpler approach based on an empirically estimated generation time interval and test positivity curve and we investigate the qualitative effects of different forms of heterogeneity in these.

Methods

Age-structured transmission model

We model transmission of SARS-CoV-2 using the stochastic age-structured branching process model described in [2]. This subsection gives a brief summary of the main model assumptions – for technical details see [2].

We use the same vaccine effectiveness and vaccine sequencing assumptions as [2]. This means that vaccine allocation is assumed to be static (we do not consider simultaneous

dynamics of community transmission and an ongoing vaccination programme) and we consider different levels of vaccine coverage. For a given level of vaccine coverage, we assume that vaccines are prioritised to the over-65-year-old age group, up to a maximum coverage of 90%; remaining vaccines are allocated uniformly to the 15-65-year-old group. For simplicity, we assume all individuals are either fully vaccinated or non-vaccinated (i.e. we do not consider the effect of people who have had a single dose). We assume the vaccine prevents infection in $e_I = 70\%$ of people, and reduced transmission by $e_T = 50\%$ in breakthrough infections. This provides an overall reduction in transmission of 85% (REF SPI-M paper). We assume that the vaccine effectiveness against symptomatic disease is the same as the vaccine effectiveness against infection e_I (this assumption will be tested in future sensitivity analysis). This does not preclude higher vaccine effectiveness against severe illness or death, although we do not investigate these outcomes in this study.

Transmission between age groups is described by a next generation matrix, whose (i, j) entry is defined to be the expected number of secondary infections in age group i due to an infectious person in age group j in the absence of interventions and given a fully susceptible population:

$$NGM_{i,j} = Uu_i t_I C_{j,i}$$

where u_i is the relative susceptibility to infection of age group i, C is a contact matrix describing mixing rates between and within age groups [4], t_I is the average infectious period and U is a constant representing the intrinsic transmissibility of the virus.

Infected individuals are categorised as either clinical or subclinical, with the clinical fraction increasing with age (see Table 1b). Clinical individuals are assigned a symptom onset time which is Gamma distributed from exposure time with mean 5.5 days and s.d. 3.3 days [5]. In the absence of interventions, we assume generation time are drawn from a Weibull distribution with mean 5.0 days and s.d. 1.9 days [6]. Subclinical individuals are assumed to be $\tau = 50\%$ as infectious as clinical individuals.

All individuals are assigned a gamma distributed random variable Y_l with mean 1 and variance $1/k$, such that the expected number of secondary cases infected by individual l given a fully

susceptible population in the absence of interventions (the individual reproduction number) is

$$R_l = (1 - V_l e_T) Y_l \sum_{j=1}^{M} NGM_{j,a_l}$$

where $V_l = 1$ if individual l is vaccinated and zero otherwise, and e_T is the vaccine effectiveness against transmission conditional on infection. The expression above is multiplied by τ if individual l is subclinical. This allows for individual heterogeneity in transmission.

Testing

Travellers are assigned curves representing the probability of testing positive as a function of time since exposure. For RT-PCR tests we use data from [4], with a peak probability of testing positive of 81% eight days after infection, and for LFT tests we use data from [7], scaled so they have a peak probability of 73% (90% of the PCR peak) and shifted so this peak occurs at the same time as the PCR curve (see Figure 1).

In addition, we assume that it is not possible to test negative by PCR and positive by LFT on the same day. To generate an LFT result, we therefore simulate the result of a putative PCR test where probability of a positive result is as shown by the blue curve in Fig. 1. If the putative PCR result is negative, we assume the LFT result is also negative. If the putative PCR result is positive, we assume the LFT result is positive with probability $P(LFT^+|PCR^+) = P^+_{LFT}(t)/P^+_{PCR}(t)$, which is the ratio of the blue curve to the red curve in Fig. 1.

The overall shape of these curves implies a protocol sensitivity of 77% (PCR) and 60% (LFT) for a test taken randomly within one week from symptom onset, and 66% (PCR) and 33% (LFT) for a test taken randomly within two weeks from symptom onset.

For the base model, we ignore individual heterogeneity in probability of testing positive at a given time after infection but test sensitivity to this assumption (see Individual Heterogeneity subsection below). We also assume that the results of multiple tests on the same individual on different days are independent. The probability of testing positive is assumed to be the same for subclinical and clinical individuals. Conditional on getting infected, the probability of testing positive is assumed to be the same for vaccinated as for non-vaccinated individuals. is assumed to be the same for vaccinated as for non-vaccinated individuals.

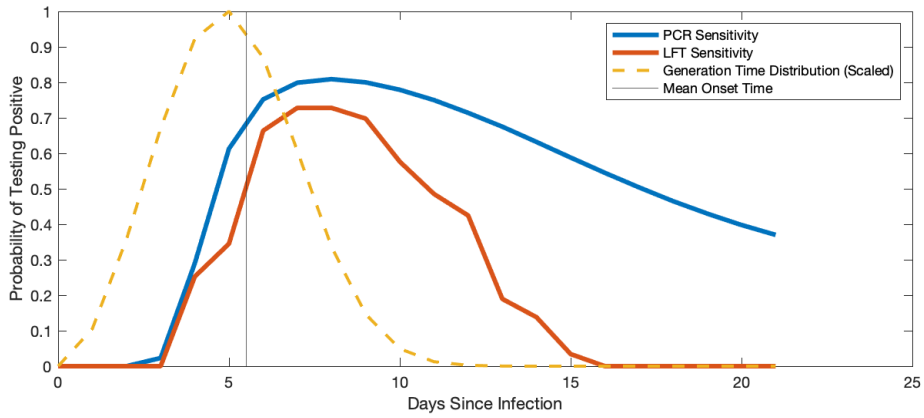

Figure 1. Assumed probability of testing positive as a function of time since infection for PCR (blue) and LFT (red). Dashed curve shows the scaled generation time distribution, showing that a large amount of transmission occurs prior to test positivity.

It is clear from Figure 1 that, under these assumptions, a significant amount of transmission occurs before the infected person has a reasonably high probability of testing positive. This may seem pessimistic but it is consistent with the fact that pre-symptomatic transmission of SARS-CoV-2 is known to be common and with empirical data showing that the probability of testing positive prior to symptom onset is smaller than after symptom onset [4].

Border interventions

We test the effects of a set of interventions depending on policy scenarios (see below) on the expected transmission from an infected traveller. We use $F_l^c(t)$ to denote the transmission rate of individual l at time t under a given intervention c, relative to their unmitigated transmission rate at time t. When $F_l^c(t) = 1$, this means individual l is not quarantined or isolated at time t; when $F_l^c(t) = 0$, this means individual l is fully isolated at time t and

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cannot transmit the virus. Note that $F_l^c(t)$ is also defined to be zero if individual l has not yet arrived at their destination, or has been prevented from travelling from pre-departure symptom checks or testing. The expected number of secondary cases caused by individual l under interventions c relative to no interventions is given by:

$$\frac{R_l^c}{R_l} = \int_0^\infty F_l^c(t)\omega(t)\,dt$$

where $\omega(t)$ is the probability density function for the generation time distribution.

Interventions can be split into three categories: vaccination status, pre-departure tests, post-arrival restrictions. We consider a few key policies for each category in Table 1. All scenarios assume a baseline level of screening passengers so that 80% of travellers who develop symptoms prior to departure are prevented from travelling, independent of any tesing requirements.

Vaccination	Pre-Departure	Post-Arrival
Fully vaccinated	No test	No requirements
Not vaccinated	PCR on day -3	PCR on days 0 & 4
	LFT on day -1	Daily LFT for 5 days
		5 day self-isolation with PCR on days 0 & 4
		5 day self-isolation with Daily LFT for 5 days
		7 days MIQ + day 5 PCR
		Full 14 day MIQ + 2 tests

Table 1. Overview of key policies considered for international travellers.

[FLOWCHART DIAGRAM TO GO HERE]

Self-isolation after arrival can occur for any one of four reasons:

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- Due to a requirement to self-isolate while asymptomatic, assumed to reduce transmission by 60% ($F_l^c(t) = c_{asymp} = 0.4$).
- Due to onset of symptoms, assumed to reduce transmission by 80% ($F_l^c(t) = c_{symp} = 0.2$), regardless of the isolation policy. Isolation is assumed to begin on the day following symptom onset. This might represent a situation where recent arrivals are contacted by public health teams to encourage monitoring of symptoms.
- Due to return of a positive test, assumed to reduce transmission by 100% ($F_l^c(t) = c_{conf} = 0$), regardless of the isolation policy. Isolation is assumed to begin on the day following the return of a positive result.
- Due to a requirement to enter MIQ, assumed to reduce transmission by 100% ($F_l^c(t) = c_{MIQ} = 0$).

Individuals isolate with the effectiveness of the strongest measure that applies at time t. This formulation assumes that all isolated individuals transmit at a reduced rate c. However, we expect average model outputs to be very similar if we instead assumed that a fraction c of isolated individuals do not transmit at all, and a fraction $1 - c$ transmit at the same rate as a non-isolated individual.

Individuals that develop symptoms after arrival seek a test with probability 80%. This test is assumed to be a PCR test taken with an exponentially distributed delay with mean 2 days after symptom onset and the result is returned the following day. If the individual is scheduled for any kind of test on the same day, they do not take the additional test.

Branching process model for community outbreaks

At each timestep of size Δt, infected individuals generate a Poisson distributed number of secondary cases with mean:

$$\lambda(t) = R_l \int_t^{t+\Delta t} F_l^c(x)\omega(x)\, dx$$

where $F_l^c(x)$ describes the reduction in transmission due to isolation or prevention of travel (see above) and $\omega(x)$ is the probability density function for the generation time distribution.

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Each secondary case is assigned an age-group i with probabilities proportional to the $a_l{}^{\text{th}}$ column of the next-generation matrix (corresponding to the index cases' age-group). These cases are assigned to the vaccinated class with probability v_i. The would-be secondary cases that are vaccinated are then thinned with probability e_I, the assumed vaccine effectiveness against infection. Population immunity due to prior infection is ignored in the model. This is reasonable because we only consider small community outbreaks and pre-existing immunity due to infection is negligible in New Zealand.

By default we assume $R_0 = 6.0$ for all simulations, approximately representing the Delta variant of SARS-CoV-2 (REF, e.g. one of the SPI-M papers) and that arriving travellers have the same age distribution and contact matrix as the New Zealand population.

We use a simplified model for case-targeted controls in the community. We assume there are initially no controls in place in the period of time before the outbreak is detected (i.e. before the first positive test result is returned). Outbreaks can be detected either via a positive test result in the infected traveller or by community testing. During the period before the outbreak is detected, we assume that symptomatic individuals in the community are tested with probability $p_{test,pre}$ 0.12. Once an outbreak has been detected, all existing and subsequent cases in the outbreak are detected with probability $p_{test,outbreak}$ 0.4 and isolated with a mean delay of 2 days after symptom onset. To model the effect of contact tracing, we also assume that cases are traced with probability p_{trace} 0.7 and isolated with a mean delay of 6 days after infection (see Table 1b).

Individual heterogeneity in probability of testing positive

In the base model, we ignore heterogeneity between individuals in the probability of testing positive at a given time. In reality, there may be variability in the timing, magnitude and duration of the probability of testing positive, and these may be correlated with individual infectiousness. This could affect the performance of different risk mitigation strategies. However, explicitly modelling these heterogeneities and correlation would require data on the probability of testing positive and infectiousness, stratified by individual and time. In the absence of detailed data on this, we consider a simplified model for individual heterogeneity.

The base model described above includes heterogeneity in transmission, via the individual parameter Y with mean 1 and variance $1/k$. To introduce heterogeneity in probability of testing positive, we let $Y = Y_1 Y_2$ where Y_1 and Y_2 are independent random variables. This characterisation decomposes individual heterogeneity in transmission into a contribution Y_1 that is independent of the probability of testing positive and a contribution Y_2 that is related to the probability of testing positive. Conceptually, Y_1 quantifies behavioural factors that drive transmission (i.e. contact rates during the infectious period), whereas Y_2 is related to biological characteristics of the viral infection (e.g. viral load) in a particular individual. By adjusting the variance of Y_1 while holding the variance of Y fixed, we can vary the extent to which individual transmission is correlated with probability of testing positive. In the base model, $Var(Y_2) = 0$ meaning there is no heterogeneity in probability of testing positive and so heterogeneity in transmission rates are entirely due to individual differences in contact rates.

To realise this model we assume Y_1 is gamma distributed with mean 1 and variance $1/k^*$ and Y_2 is normally distributed with mean 1 and varaicne σ^2, truncated to non-negative values. If we set $k^* = k(1+\sigma^2)/(1-k\sigma^2)$, then provided σ^2 is sufficiently small, Y is approximately gamma distributed with mean 1 and variance $1/k$, as for the base model. A test result for individual l at time t is then generated as an independent Bernoulli random variable with mean $\frac{y_{2,l}P^+(t)}{1-(1-y_{2,l})P^+(t)}$, where $y_{2,l}$ is the value of the random variable Y_2 for individual l and $P^+(t)$ is the relevant test positivity curve for either PCR or LFT shown in Figure 1.

Model Outputs

For each set of interventions c, we run $N = 10{,}000$ simulations, each initialised with one infected traveller. The traveller is assigned an age-group with a frequency proportional to the New Zealand age-structure, an infection time uniformly randomly distributed in the 14 days prior to arrival, and a clinical status that depends on age. The simulation returns the

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transmission potential of the infected traveller (R_l^c) and a list of any infections in the community. From these simulations, we report three model outputs defined as follows.

Output (1) is the transmission potential of infected arrivals under interventions c relative to the transmission potential in the absence of interventions. This is defined as $\overline{R_l^c}/\overline{R_l^0}$ where the bar denotes the mean of N simulations.

Output (2) is the proportion of simulations meeting each of the following four criteria: (i) the infected traveller causes any onward transmission in the community; (ii) the infected traveller causes onward transmission in the community and is never detected; (iii) the infected traveller leads to an outbreak that reaches 5 infections; (iv) the infected traveller leads to a large outbreak that reaches 50 infections. Note that because the reproduction number is significantly greater than 1, even at the highest vaccine coverage level considered (90% of over-15s), outbreaks that reach 50 infections are almost certain to continue to grow indefinitely until control measures are introduced (or there is a build-up of population immunity). The criteria of 50 infections is arbitrary, but is a convenient point at which to terminate simulations and indicates that community transmission has become established. For context, this threshold is approximately the number of people who were already infected at the time the Auckland outbreak in August 2020 was detected.

Finally, output (3) is the number of infected travellers who would be expected to result in one large outbreak (that reaches 50 cases from one traveller). If, for example, an average of one outbreak *per month* is tolerable, then this is the number of infected travellers who would be tolerated per month. This is equal to the reciprocal of the probability that an infected arrival starts a large outbreak.

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Parameter	Value
Basic reproduction number in the absence of control	$R_0 = 6$
Relative transmission rate for isolated individuals:	
- asymptomatic / pre-symptomatic	$c_{asym} = 0.4$
- symptomatic	$c_{symp} = 0.2$
- confirmed cases	$c_{conf} = 0$
- in MIQ	$c_{MIQ} = 0$
Incubation period	Mean 5.5 days, s.d. 3.3 days
Generation interval	Mean 5.0 days, s.d. 1.9 days
Relative infectiousness of subclinical individuals	$\tau = 0.5$
Heterogeneity in individual reproduction number	$k = 0.5$
Vaccine effectiveness:	
- against infection	$e_I = 0.7$
- against transmission in breakthrough infection	$e_T = 0.5$
Probability of a clinical community case being tested:	
- before an outbreak is first detected	$p_{test,pre} = 0.12$
- after an outbreak is detected	$p_{test,outbreak} = 0.4$
Mean time from symptom onset to test result:	
- before an outbreak is first detected	~~2~~ 4 days
- after an outbreak is detected	~~2~~ 4 days
Probability of a community case being detected via contact tracing	$p_{trace} = 0.7$
Mean time from infection to quarantine for traced contacts	6 days
Probability of testing positive by PCR on days $[1, \dots, 21]$ after infection	[0, 0.01, 0.04, 0.33, 0.62, 0.75, 0.79, 0.80, 0.79, 0.77, 0.73, 0.70, 0.66, 0.62, 0.57, 0.52, 0.48, 0.44, 0.40, 0.37, 0.34]
Probability of testing positive by LFT on being PCR positive on days $[4, \dots, 15]$ after infection	[0.25, 0.35, 0.66, 0.73, 0.73, 0.70, 0.58, 0.49, 0.42, 0.19, 0.14, 0.03]

Age-specific parameters																
Age (yrs)	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75+
% of popn	5.98	6.39	6.56	6.17	6.59	7.40	7.44	6.62	6.08	6.41	6.43	6.38	5.77	4.90	4.24	6.64
Pr(clinical) (%)	54.4	55.5	57.7	59.9	62.0	64.0	65.9	67.7	69.5	71.2	72.7	74.2	75.5	76.8	78.0	80.1
Susceptibility*	0.46	0.46	0.45	0.56	0.80	0.93	0.97	0.98	0.94	0.93	0.94	0.97	1.00	0.98	0.90	0.86

Table 1b. Parameter values used in the model. *Susceptibility for age group i is stated relative to susceptibility for age 60-64 years.

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Results

Relative Transmission Potential

The relative transmission potential measures the reduction in the expected number of secondary cases per infected traveller as a result of a given border intervention c. By construction, the relative transmission potential measures of the effectiveness of a given border intervention in reducing risk, independent of the assumed value of R_0 and of the level of vaccine coverage in the domestic population. For example, a set of interventions for which the relative transmission potential is 0.6 means that an individual infected traveller under this intervention is on average 60% as risky as they would be with no interventions.

Table 2 gives the relative transmission potential of an average infected traveller under a given border policy. All results are relative to the same baseline, representing the transmission potential of a non-vaccinated traveller that faces no interventions other than a pre-departure symptom check. Conditional on being infected, a vaccinated individual is assumed to be approximately 50% as infectious as a non-vaccinated individual (Table 1b). However, it is important to note that these individuals, depending on the vaccination rates and prevalence of infection in country of origin, are less likely to be infected than a non-vaccinated person in the first place.

The introduction of regular symptom checks post-arrival and isolation (assumed to be 80% effective from the day following symptom onset) for symptomatic arrivals reduces the transmission potential to 77% of the baseline (unmitigated) transmission potential for non-vaccinated travellers and 39% for vaccinated travellers.

The addition of a pre-departure testing requirement provides a relatively small reduction in transmission potential (for vaccinated travellers from 39% with no pre-departure testing to 38% for PCR on day -3 or 36% for LFT on day -1). Although pre-departure testing and symptom checks screens out a significant number (approximately 34% for symptom-checks only, 54% with the addition of either test) of travellers, many of these travellers would have been

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towards the end of their infectious period by the time they arrived at their destination. This is why the reduction in transmission potential is relatively small. The small difference between the effect of a PCR tests on day -3 and a LFT test on day -1 suggests the reduced sensitivity of the LFT is roughly offset by the fact it can be done closer to the time of departure.

Of the post-arrival testing strategies, a daily LFT for 5 days is more effective (reducing transmission potential from 39% to 23% for vaccinated arrivals) than PCR tests on day 0 and day 4 (39% to 33%). This shows that, under the assumed test characteristics, the lower sensitivity of LFT tests is outweighed by the increased frequency of testing and faster return of results.

Adding a requirement for five days self-isolation after arrival further reduces transmission potential (from 33% to 15% with the PCR testing strategy and from 23% to 10% with the LFT strategy, for vaccinated arrivals). Finally, a seven day stay in MIQ with two PCR tests reduces transmission potential to approximately 0.2% for vaccinated travellers, and a fourteen day stay in MIQ with two PCR tests reduces risk to near zero.

Risk of Onward Transmission

Table 3 gives the probability that an infected traveller leads to any onward transmission in the community and Table 4 gives the probability that an infected traveller leads to any onward transmission and is not detected by testing. Table 5 gives the probability that an infected traveller starts an outbreak that reaches at least 5 cases, and Table 6 gives the probability that an infected traveller starts an outbreak that reaches at least 50 cases. These risks all decrease as the vaccine coverage in the resident population increases. The latter two tables assume a moderately effective contact tracing process begins once an infection has been detected (either via a positive test result in the traveller who triggered the outbreak or a detection via community testing). The results are presented for both vaccinated and non-vaccinated travellers in the tables, although we focus on vaccinated travellers in the results discussed below.

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When only pre-departure symptom checks are included, there is a 26% chance that an infected traveller leads to onward transmission (both all & undetected) for a fully susceptible population (i.e. no vaccine coverage). This decreases to 19% when 90% of the domestic population aged 15-years or over are vaccinated. Note that population vaccine coverage only reduces the risk of onward transmission due to the infection blocking aspect of the vaccine, which is assumed to have an effectiveness of $e_I = 70\%$. The risk of an outbreak to a certain size (see Tables 5 and 6 described below) is further reduced by the transmission reducing aspect of the vaccine

The addition of post-arrival symptom checks results in a modest reduction in the probability of onward transmission (23% without domestic vaccination, decreasing to 17% at 90% coverage of over-15s). This decreases to 22%/17% with the addition of a pre-departure PCR test, or to 21%/15% with the addition of a pre-departure LFT test.

Consistent with the results in Table 2, daily LFTs for 5 days after arrival makes the risk of onward transmission smaller (16% with no vaccine coverage, dropping to 11% at 90% coverage of over-15s) than PCR tests on day 0 and day 4 (21% with no vaccine coverage dropping to 15% at 90% coverage of over-15s). The daily LFT strategy also performs better at preventing onward transmission where the infection in the traveller is not detected (2.4% for LFT compared to 3.2% for PCR with no domestic vaccination), although see below for effects of individual heterogeneity.

When five days of self-isolation are required we again find that daily LFT tests perform better at preventing any onward transmission (7.6% for LFT compared to 11% for PCR with no domestic vaccination), and better at preventing onward undetected transmission (2.0% for LFT compared to 2.8% for PCR).

Comparing Tables 5 and 6 suggests that, in a non-vaccinated population, most outbreaks that reach five cases also go on to reach fifty cases, as the respective probabilities are very similar. These scenarios assume effective contact tracing is implemented once an outbreak is detected, so while vaccination levels are low, additional controls would almost always be necessary to control an outbreak.

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High levels of community vaccine coverage decreases the risk that a vaccinated traveller with only pre-departure symptom checking starts a large outbreak from 17% with no vaccination, to 5.5% with 90% of 15+ year-olds vaccinated. Introducing a pre-departure LFT and domestic symptom checks decreases this to 3.8%. Further introducing a daily LFT for 5 days post arrival takes this to 2.5%, or a PCR test on day 0 and 4 takes this to 3.5%. Including 5 days of self-isolation reduces the risk with LFT tests to 1.4% and the risk with PCR tests to 1.9%. These results can also be interpreted in terms of the number of infected travellers that are expected to lead to one large outbreak (Table 7).

Aside from those involving MIQ, the only scenario that consistently tolerates more than 50 infected travellers per large outbreak is 5 day self-isolation with daily LFTs and 80%+ domestic vaccine coverage, or 5 day self-isolation with two PCR tests and 90% vaccine coverage. There is no scenario where domestic vaccine coverage is below 80% of over 15-year-olds and more than 50 infected travellers can be allowed to enter without MIQ.

Effects of individual heterogeneity in probability of testing positive

Results for the model with individual heterogeneity in the probability of testing positive are provided in Supplementary Material. Overall, the effects of heterogeneity in probability of testing positive appear to be a relatively small part of the overall stochasticity of the simulation results. If there is heterogeneity between individuals in the probability of testing positive by LFT, this may decrease the performance of strategies based on daily LFT testing because some infected individuals can be missed, even when tested on five consecutive days. Further work is needed to more completely understand the sensitivity of the results to heterogeneity, but at this stage it appears to be a relatively small effect.

Mixed LFT and PCR strategy

Previous results suggest that, if we assume a high level of variability in LFT positivity, then two PCR tests taken on days 0 and 4 may be more effective at preventing undetected onward transmission than daily LFTs on days 0 to 4. This arises from the increased ability of a PCR test

to detect the virus later in the infection. This implies that a strategy of daily LFTs with a day 4 PCR may be best in reducing both onward transmission and undetected onward transmission.

We compare three scenarios: (1) the standard PCR on day 0 and 4, (2) the standard daily LFT for 5 days, and (3) a daily LFT on days 0 to 3 with a PCR test on day 4. When considering remaining transmission potential, strategy (1) is the worst option with 41% remaining. Strategies (2) and (3) are very similar, with around 23% of transmission potential remaining in both (for a vaccinated arrival that takes a pre-departure PCR test and enters a non-vaccinated population). This pattern holds when considering any onward transmission.

However, when comparing the probability of undetected onward transmission, the mixed testing strategy performs significantly better (1.2%) compared to the daily LFT (2.0%) and two PCR tests (4.0%). This suggests that, while the PCR test has a longer delay to returning results, the additional sensitivity later in infection when an individual is less likely to still transmit offsets this.

Discussion

We have modelled the effect of different border controls on the risk of international travellers infected with SARS-CoV-2 transmitting the virus and triggering community outbreaks. Potential border measures include a requirement for travellers to be vaccinated, different combinations of pre-departure testing and post-arrival testing and quarantine. We investigated outcomes at different levels of vaccine coverage in the domestic population.

Our results should be interpreted as estimates of the relative effectiveness of alternative mitigation strategies, rather than absolute predictions of risk. For example, the model estimates that pre-departure tests alone have a relatively small impact on the risk of a community outbreak. Adding post-arrival testing requirements provides a larger benefit and can cut the risk by around 50% relative to no testing. A further requirement for 5 days of self-isolation at home can cut the risk to around one third of the risk without mitigations. This

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result assumes that self-isolation is 40% effective in reducing transmission for asymptomatic or pre-symptomatic individuals and 80% effective for symptomatic individuals. The model results also clearly show the progressive reduction in risk as vaccine coverage in the domestic population increases: achieving 90% vaccine coverage amongst over-15-year-olds cuts the risk of a community outbreak by roughly a factor of 3.

Our results apply to the risks per infected traveller. The other key determinant of overall risk is the number of infected travellers, which is a product of the prevalence of infection amongst travellers and the travel volume. The latter variable is crucial because, while current travel volume is approximately 2,500 arrivals to New Zealand per week, this could increase substantially with the relaxation of travel eligibility and quarantine requirements. For example, a hypothetical scenario with 50,000 arrivals per week (i.e. around 50% of pre-pandemic travel volume) and a prevalence of 0.15 infections per 1000 travellers would mean around 7.5 infected arrivals per week. Under the more optimistic scenarios with high vaccine coverage and 5-day self-isolation and testing requirements , the model estimates the risk of a community outbreak to be in the region of 2% per infected arrival. This would translate to around one new community outbreak every 6-7 weeks.

If vaccine coverage is sufficiently high, the majority of these outbreaks may be stamped out with targeted measures like intensive community testing and contact tracing (Steyn et al 2021). However, this would likely require significantly higher capacity than has been used in previous outbreaks in New Zealand. In addition, some outbreaks would likely require broader interventions or even localised lockdowns, particularly if they affected population groups with relative low vaccine coverage or high contact rates. This suggests a staged approach to relaxing travel restrictions with a gradual as opposed to a sudden increase in travel volume, allowing case management and outbreak control systems to be tested.

The assumed reduction in transmission from individuals in self-isolation at home does not capture any specific effects, such as the increased relative likelihood of transmission to household contacts. Policies such as requiring all household contacts of self-isolating travellers to be vaccinated or mandating the collection of contact tracing information would further reduce risk. However, the effectiveness of home isolation is largely untested in the

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New Zealand context. Analysis of contact tracing data from March 2021 suggested that the introduction of a self-isolation requirement for international arrivals reduced transmission by 35% (James et al 2021), although this based on a small dataset that may not be representative of future cohorts of travellers.

Lateral flow rapid antigen tests have not previously been used in New Zealand. Trialling these alongside PCR tests in MIQ facilities and frontline border workers would allow for the collection of valuable real-world data to evaluate their sensitivity at different times relative to symptom onset.

The over-dispersed nature of SARS-CoV-2 transmission implies many infected people do not transmit the virus, or only infect one or two others, whereas a small minority of cases can infect a large number of other people. This means that, although the probability of an individual transmitting the virus may be low, the ones who do transmit can lead to outbreaks that grow faster than an average would suggest.

Including individual heterogeneity in the probability of testing positive by LFT can make strategies based on daily LFT testing slightly less effective than a two-test PCR strategy at reducing onward transmission from an undetected case. This indicates that there is some uncertainty as to the performance of the LFT strategy relative to the PCR strategy. Although the model results do not clearly favour the LFT-only strategy, they suggest that a daily LFT strategy with a PCR test on the final day could combine the best of both testing methods. This benefits from the high-frequency testing enabled by LFT, with a final PCR test giving an opportunity to detect cases who may have been missed by LFT.

We have assumed that vaccinated and non-vaccinated infected individuals have the same probability of developing symptoms of COVID-19. If in reality vaccinated infected people are less likely to develop symptoms, the effectiveness of post-arrival symptom checks and symptom-triggered testing in vaccinated travellers will be less than in the results shown here. However, this reduced effectiveness may be offset if likelihood of developing symptoms is correlated with infectiousness. Further work is needed to investigate this.

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Arrival Testing	Pre-Depart	Remaining Transmission Potential (Non-vaccinated Travellers)	Remaining Transmission Potential (Vaccinated Travellers)
Pre-departure Symptom Check Only		100%	50%
Regular Symptom Checks	No Test	77%	39%
	PCR on Day -3	76%	38%
	LFT on Day -1	73%	36%
PCR on days 0 & 4	No Test	66%	33%
	PCR on Day -3	65%	33%
	LFT on Day -1	63%	32%
Daily LFT for 5 days	No Test	45%	23%
	PCR on Day -3	45%	23%
	LFT on Day -1	44%	22%
5 day isolation + PCR on days 0 & 4	No Test	29%	15%
	PCR on Day -3	29%	14%
	LFT on Day -1	28%	14%
5 day isolation + Daily LFT for 5 days	No Test	20%	10%
	PCR on Day -3	20%	10%
	LFT on Day -1	20%	10%
7 Day MIQ + PCR on days 0 & 4	No Test	0.3%	0.2%
	PCR on Day -3	0.4%	0.2%
	LFT on Day -1	0.3%	0.2%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%

Table 2. Average remaining transmission potential of infected travellers under various border controls. All scenarios assume pre-departures symptom checks, regular post-arrival symptom checks, and symptom-triggered testing are implemented, with the exception of the first row.

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		Community vaccine coverage									
		Non-vaccinated travellers					Vaccinated travellers				
Arrival	**Pre-Depart**	**0%**	**60%**	**70%**	**80%**	**90%**	**0%**	**60%**	**70%**	**80%**	**90%**
No measures	Symptom check	26%	22%	21%	20%	19%	20%	17%	16%	15%	14%
Regular symptom checks	Symptom check	23%	20%	19%	18%	17%	18%	15%	14%	13%	12%
	PCR on day -3	22%	19%	19%	18%	17%	17%	14%	14%	13%	12%
	LFT on day -1	21%	18%	17%	16%	15%	16%	13%	13%	12%	11%
PCR on days 0 & 4	Symptom check	21%	18%	17%	16%	15%	16%	13%	12%	12%	11%
	PCR on day -3	21%	18%	17%	16%	15%	16%	13%	12%	11%	11%
	LFT on day -1	19%	16%	16%	15%	14%	15%	12%	12%	11%	10%
Daily LFT for 5 days	Symptom check	16%	13%	13%	12%	11%	12%	9.6%	9.0%	8.4%	7.7%
	PCR on day -3	16%	13%	13%	12%	11%	12%	9.5%	9.0%	8.3%	7.6%
	LFT on day -1	15%	13%	12%	11%	11%	11%	9.2%	8.7%	8.1%	7.4%
5 day isolation + PCR on days 0 & 4	Symptom check	15%	12%	12%	11%	10%	11%	8.3%	7.7%	7.0%	6.3%
	PCR on day -3	15%	12%	11%	11%	9.7%	10%	8.1%	7.5%	6.9%	6.2%
	LFT on day -1	14%	11%	11%	10%	9.3%	10%	7.8%	7.2%	6.6%	6.0%
5 day isolation + Daily LFT for 5 days	Symptom check	11%	8.9%	8.4%	7.8%	7.1%	7.6%	5.9%	5.4%	5.0%	4.5%
	PCR on day -3	11%	8.8%	8.3%	7.7%	7.0%	7.6%	5.8%	5.4%	4.9%	4.4%
	LFT on day -1	11%	8.5%	8.0%	7.5%	6.8%	7.3%	5.6%	5.2%	4.8%	4.3%
7 Day MIQ + PCR on days 0 & 4	Symptom check	0.4%	0.3%	0.3%	0.2%	0.2%	0.3%	0.2%	0.2%	0.1%	0.1%
	PCR on day -3	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%
	LFT on day -1	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%
14 Day MIQ + 2x PCR on days 3 and 12	Symptom check	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on day -3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on day -1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 3. Probability of any onward local transmission from an infected traveller. Community vaccine coverage refers to the percentage of over 15-year-olds that are fully vaccinated in the community. All community vaccine coverage scenarios (except 0%) assume 90% of over 65-year-olds are fully vaccinated, with the remaining vaccinated individuals are distributed uniformly among the 15-64 year-olds.

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Non-vaccinated travellers						
		Community vaccine coverage				
Arrival	**Pre-Depart**	**0%**	**60%**	**70%**	**80%**	**90%**
Pre-departure Symptom Check Only		26%	22%	21%	20%	19%
Regular Symptom Checks	No Test	16%	13%	13%	12%	11%
	PCR on Day -3	15%	13%	12%	12%	11%
	LFT on Day -1	13%	12%	11%	11%	9.9%
PCR on days 0 & 4	No Test	3.2%	2.8%	2.7%	2.6%	2.4%
	PCR on Day -3	3.3%	2.9%	2.8%	2.6%	2.5%
	LFT on Day -1	3.2%	2.8%	2.7%	2.6%	2.5%
Daily LFT for 5 days	No Test	2.4%	2.1%	2.1%	2.0%	1.9%
	PCR on Day -3	2.3%	2.1%	2.0%	1.9%	1.8%
	LFT on Day -1	2.3%	2.1%	2.0%	1.9%	1.8%
5 day isolation + PCR on days 0 & 4	No Test	2.8%	2.3%	2.2%	2.1%	1.9%
	PCR on Day -3	2.6%	2.2%	2.1%	2.0%	1.9%
	LFT on Day -1	2.7%	2.3%	2.2%	2.0%	1.9%
5 day isolation + Daily LFT for 5 days	No Test	2.0%	1.7%	1.6%	1.6%	1.5%
	PCR on Day -3	2.0%	1.7%	1.6%	1.6%	1.5%
	LFT on Day -1	2.0%	1.7%	1.6%	1.5%	1.4%
7 Day MIQ + PCR on days 0 & 4	No Test	0.4%	0.3%	0.2%	0.2%	0.2%
	PCR on Day -3	0.4%	0.3%	0.3%	0.2%	0.2%
	LFT on Day -1	0.4%	0.3%	0.2%	0.2%	0.2%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%	0.0%	0.0%	0.0%

Vaccinated travellers						
		Community vaccine coverage				
		0%	**60%**	**70%**	**80%**	**90%**
No Symptom Checks		20%	17%	16%	15%	14%
Regular Symptom Checks	No Test	12%	9.7%	9.2%	8.6%	7.9%
	PCR on Day -3	12%	9.6%	9.0%	8.4%	7.8%
	LFT on Day -1	10%	8.6%	8.1%	7.6%	7.0%
PCR on days 0 & 4	No Test	2.7%	2.2%	2.1%	2.0%	1.8%
	PCR on Day -3	2.7%	2.2%	2.1%	2.0%	1.8%
	LFT on Day -1	2.8%	2.3%	2.2%	2.1%	1.9%
Daily LFT for 5 days	No Test	2.0%	1.7%	1.6%	1.5%	1.4%
	PCR on Day -3	1.9%	1.6%	1.6%	1.5%	1.4%
	LFT on Day -1	1.9%	1.6%	1.6%	1.5%	1.4%
5 day isolation + PCR on days 0 & 4	No Test	1.9%	1.5%	1.4%	1.3%	1.2%
	PCR on Day -3	2.0%	1.6%	1.5%	1.4%	1.2%

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	LFT on Day -1	1.8%	1.5%	1.4%	1.3%	1.2%
5 day isolation + Daily LFT for 5 days	No Test	1.5%	1.2%	1.2%	1.1%	1.0%
	PCR on Day -3	1.5%	1.2%	1.2%	1.1%	1.0%
	LFT on Day -1	1.5%	1.3%	1.2%	1.1%	1.0%
7 Day MIQ + PCR on days 0 & 4	No Test	0.2%	0.1%	0.1%	0.1%	0.1%
	PCR on Day -3	0.2%	0.1%	0.1%	0.1%	0.1%
	LFT on Day -1	0.2%	0.1%	0.1%	0.1%	0.1%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4. Probability of any onward transmission from an infected traveller who is never detected. Percentages 0%, 60%, 70%, 80%, and 90% refer to the percentage of over 15-year-olds that are vaccinated in the community. All scenarios except 0% assume 90% of over 65-year-olds are vaccinated, with the remaining doses distributed among the 15-64 year-olds.

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Vaccinated travellers						
		Community vaccine coverage				
		0%	60%	70%	80%	90%
Pre-departure Symptom Check Only		17%	13%	11%	9.4%	7.8%
Regular Symptom Checks	No Test	15%	10%	9.3%	7.9%	6.6%
	PCR on Day -3	14%	10%	8.7%	8.0%	6.3%
	LFT on Day -1	13%	9.7%	8.3%	7.3%	5.6%
PCR on days 0 & 4	No Test	13%	8.8%	8.1%	7.0%	5.5%
	PCR on Day -3	13%	8.9%	8.3%	6.6%	5.5%
	LFT on Day -1	12%	8.4%	7.8%	6.4%	5.0%
Daily LFT for 5 days	No Test	9.5%	6.6%	5.7%	4.8%	3.8%
	PCR on Day -3	9.2%	6.3%	5.9%	5.1%	3.9%
	LFT on Day -1	8.9%	6.1%	5.7%	4.7%	3.7%
5 day isolation + PCR on days 0 & 4	No Test	8.0%	5.2%	5.0%	3.6%	2.6%
	PCR on Day -3	7.7%	5.2%	4.4%	3.7%	2.7%
	LFT on Day -1	7.6%	4.8%	4.5%	3.4%	2.8%
5 day isolation + Daily LFT for 5 days	No Test	5.6%	3.7%	3.3%	2.5%	2.1%
	PCR on Day -3	5.7%	3.2%	3.0%	2.4%	1.9%
	LFT on Day -1	5.6%	3.7%	3.2%	2.4%	2.0%
7 Day MIQ + PCR on days 0 & 4	No Test	0.1%	0.1%	0.1%	0.1%	0.1%
	PCR on Day -3	0.1%	0.1%	0.1%	0.1%	0.0%
	LFT on Day -1	0.1%	0.1%	0.1%	0.1%	0.0%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%	0.0%	0.0%	0.0%

592 **Table 5.** Probability of an infected traveller starting an outbreak leading to at least 5
593 infections.
594

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Vaccinated travellers						
		Community vaccine coverage				
		0%	60%	70%	80%	90%
Pre-departure Symptom Check Only		17%	12%	9.7%	7.6%	5.5%
Regular Symptom Checks	No Test	15%	9.4%	8.3%	6.6%	4.4%
	PCR on Day -3	14%	9.5%	7.9%	6.6%	4.1%
	LFT on Day -1	13%	8.9%	7.4%	5.9%	3.8%
PCR on days 0 & 4	No Test	13%	8.2%	7.4%	5.8%	3.7%
	PCR on Day -3	12%	8.3%	7.4%	5.3%	3.9%
	LFT on Day -1	12%	7.7%	7.1%	5.3%	3.5%
Daily LFT for 5 days	No Test	9.4%	6.0%	5.1%	4.0%	2.8%
	PCR on Day -3	9.2%	5.9%	5.3%	4.2%	2.6%
	LFT on Day -1	8.7%	5.7%	5.2%	3.7%	2.5%
5 day isolation + PCR on days 0 & 4	No Test	7.9%	4.9%	4.5%	2.9%	1.7%
	PCR on Day -3	7.7%	5.0%	3.8%	3.1%	1.7%
	LFT on Day -1	7.4%	4.5%	4.0%	2.8%	1.9%
5 day isolation + Daily LFT for 5 days	No Test	5.5%	3.5%	2.9%	2.0%	1.6%
	PCR on Day -3	5.6%	3.1%	2.7%	2.0%	1.3%
	LFT on Day -1	5.6%	3.5%	3.0%	1.8%	1.4%
7 Day MIQ + PCR on days 0 & 4	No Test	0.1%	0.1%	0.1%	0.1%	0.1%
	PCR on Day -3	0.1%	0.0%	0.1%	0.1%	0.0%
	LFT on Day -1	0.1%	0.1%	0.0%	0.0%	0.0%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%	0.0%	0.0%	0.0%

595 **Table 6.** Probability of an infected traveller starting a large outbreak leading to at least 50
596 infections.
597

NOT YET PEER REVIEWED

Vaccinated travellers						
		Community vaccine coverage				
		0%	60%	70%	80%	90%
Pre-departure Symptom Check Only		6	9	10	13	18
Regular Symptom Checks	No Test	7	11	12	15	23
	PCR on Day -3	7	11	13	15	24
	LFT on Day -1	8	11	13	17	27
PCR on days 0 & 4	No Test	8	12	14	17	27
	PCR on Day -3	8	12	13	19	26
	LFT on Day -1	8	13	14	19	28
Daily LFT for 5 days	No Test	11	17	20	25	36
	PCR on Day -3	11	17	19	24	39
	LFT on Day -1	11	18	19	27	40
5 day isolation + PCR on days 0 & 4	No Test	13	21	22	35	58
	PCR on Day -3	13	20	27	33	59
	LFT on Day -1	13	22	25	36	52
5 day isolation + Daily LFT for 5 days	No Test	18	28	34	51	65
	PCR on Day -3	18	33	37	50	80
	LFT on Day -1	18	29	34	54	74
7 Day MIQ + PCR on days 0 & 4	No Test	769	769	1000	909	1000
	PCR on Day -3	1000	1000	1000	1000	1000
	LFT on Day -1	714	1000	1000	1000	1000
14 Day MIQ + 2x PCR on days 3 and 12	No Test	1000	1000	1000	1000	1000
	PCR on Day -3	1000	1000	1000	1000	1000
	LFT on Day -1	1000	1000	1000	1000	1000

598 **Table 7**. Expected number of infected travellers per large outbreak. Due to small numbers the
599 maximum size considered is 1,000 infected travellers. In many of these cases it is possible to
600 allow more.
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Visualising the effect of restrictions on travellers

The results in Table 2 of the main paper give the relative transmission potential of travellers under various restrictions, compared to a traveller that only faces a pre-departure symptom check. This “baseline” scenario is represented by the red curve in Figure S1. The relative transmission potential of an individual that also has a pre-departure PCR test and high symptom awareness post-arrival, for example, is given by the relative area under the purple curve to the area under the red curve.

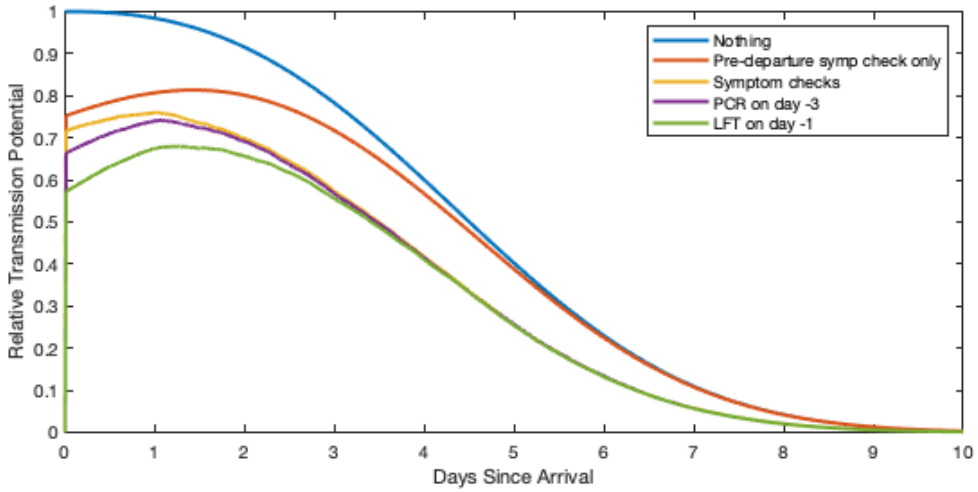


Figure S1. Relative infectiousness as a function of days since arrival. Control measures considered are all pre-departure only + post-arrival symptom awareness.

Implications of figure S1:

- Pre-departure symptom checks reduce risk the most in the first few days after arrival
    - In doing so they shift the peak risk (in the absence of other measures) to around 1.4 days after arrival
- Post-arrival symptom awareness noticeably reduces risk, especially from 2 days after arrival
- The addition of a PCR test 3 days prior to departure reduces transmission risk a small amount in the first day, but the effect is small
- A LFT on the day of departure has a greater effect than the PCR, and the benefit of this test also lasts longer. By day 4 there is no noticeable effect on risk from either.

Figure S2 considers additional testing and isolation measures.

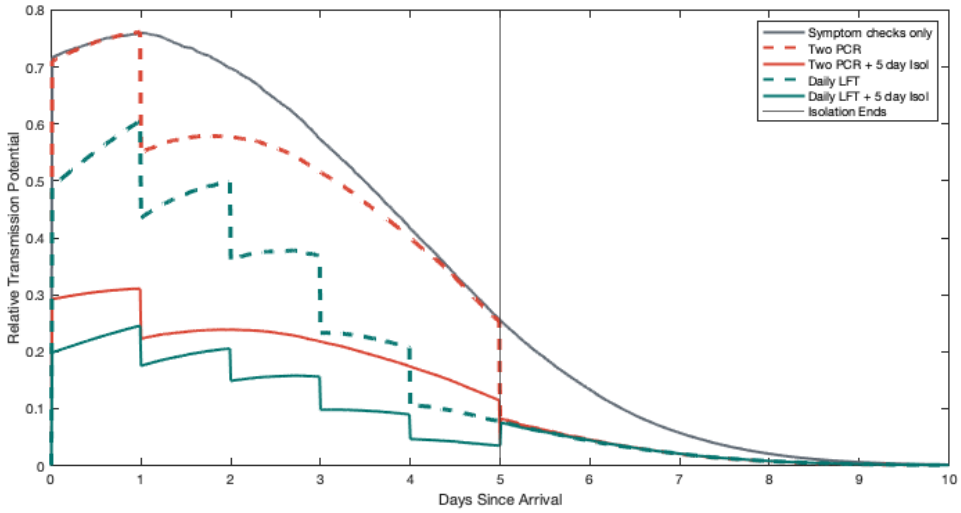


Figure S2. Relative infectiousness as a function of days since arrival.

Implications of figure S2:

- The 1-day delay in returning a day 0 (arrival) highly sensitive PCR test is **significantly** offset by the immediate results and isolation from a day 0 less sensitive LFT. Furthermore, the second LFT test on day 1 offsets the lower sensitivity.
    - A policy of isolation (or even MIQ) until results have been returned would remove a large amount of transmission potential in that first day.
- There is still a significant amount of transmission potential remaining after day 5.
    - Even if isolation was perfect (or 5 day MIQ was used) + either testing regime, a non-neglible amount of risk would remain
- The remaining transmission potential after the conclusion of the two testing regimes is about the same. This is a coincidence, but suggests that the *overall sensitivity* of the two testing regimes is estimated to be roughly equal.
    - Less surprisingly, as there is no interaction between tests & isolation strategy, the remaining transmission potential after someone finishes isolation is modelled to be the same as the remaining transmission potential of someone who never entered isolation.

Distribution of Secondary Cases from an Infected Traveller

[Caution: more trials are needed to decrease stochasticity of some of these results]

Tables S1 and S2 give the distribution of the number of secondary cases caused by an infected traveller under each policy. While increasing stringency of controls does decrease the likelihood of any outbreak (P>=1), there is still a chance of large outbreaks occurring even when self-isolation is required. This is because the modelled (heavy-tailed) individual heterogeneity in transmission is sufficiently large to counteract the (linear) reduction in transmission from isolation. **If restrictions meant that no individual had contact with this many people, then our model may be pessimistic.**

Policy	**P(0)**	**P(>=1)**	**P(>=2)**	**P(>=5)**	**P(>=10)**
Pre-departure symptom check only	83%	17%	10%	3.6%	0.94%
PCR on day 0 & 4	85%	15%	8.6%	3.0%	0.83%
5x LFT on days 0 to 4	89%	11%	6.2%	1.8%	0.5%
PCR on day 0 & 4, 5 day isolation	89%	11%	4.7%	0.78%	0.08%
5X LFT on days 0 to 4, 5 day isolation	93%	7.1%	2.9%	0.43%	0.08%

Table S1. Outbreak size distribution for each policy under **no domestic vaccination**

Policy	**P(0)**	**P(>=1)**	**P(>=2)**	**P(>=5)**	**P(>=10)**
Pre-departure symptom check only	88%	12%	5.3%	1.0%	0.09%
PCR on day 0 & 4	89%	11%	4.5%	0.81%	0.11%
5x LFT on days 0 to 4	93%	7.2%	2.9%	0.46%	0.04%
PCR on day 0 & 4, 5 day isolation	94%	6.1%	1.7%	0.15%	0.03%
5X LFT on days 0 to 4, 5 day isolation	96%	4.1%	1.1%	0.1%	0.01%

Table S2. Outbreak size distribution for each policy under **90% vaccination coverage of 15+ year-olds**

Implications of detecting infection in the traveller

Tables 3 & 4 in the main paper consider the probability that an infected traveller leads to any onward transmission, and any onward transmission where the traveller themselves are not detected. By detecting infection in the arriving traveller, even when onward transmission does occur, the traveller can be isolated faster and the contact tracing process can begin earlier. Table S3 gives the probability of a large outbreak occurring, conditional on whether the infected traveller was detected or not.

	-	No Vax		70% of 15+		90% of 15+	
	P(det)	Not	Det	Not	Det	Not	Det
Pre-departure symptom check only	0.68	28%	6.5%	16%	3.6%	8.6%	2.2%
PCR on day 0 & 4	0.94	33%	11%	18%	5.5%	9.1%	3.3%
5x LFT on days 0 to 4	0.94	29%	7.9%	14%	4.3%	7.8%	2.2%
PCR on day 0 & 4, 5 day isolation	0.94	23%	6.5%	11%	3.3%	5.9%	1.3%
5x LFT on days 0 to 4, 5 day isolation	0.94	19%	4.7%	10%	2.1%	5.2%	1.1%

Table S3. Probability of a large outbreak occurring conditional on whether the infected traveller was detected or not. Strategies ordered in increasing overall effectiveness.

There are two effects that may cause undetected travellers to pose greater risk:

1. A detected traveller is likely to be isolated earlier and is therefore less likely to cause any transmission
2. Detecting an outbreak in the traveller gives the contact tracing system a head start

Next steps: Quantify which of these two effects matters most, then link with local testing and contact tracing to get an idea of how important this is.

Time to Reach 50 Infections

Given a single seed case this can be calculated fairly trivially. Assuming R0 = 6.0 and no vaccination, it takes a median of 13 days (IQR 10, 17) to reach 50 infections (from exposure of the single seed case). With 70% coverage of over 15-year-olds it takes a median of 19 days (IQR 15, 25) to reach 50 infections. Finally, with 90% coverage of over 15-year-olds it takes a median of 23 days (IQR 18, 29) to reach 50 infections.

The above results assume that the outbreak is not detected in the arriving traveller. If we assume the contact tracing system kicks in on the same day as the seed case is exposed, in a non-vaccinated population the median increases slightly to 14 days (IQR 11, 18). The effect is also seen when 70% of over-15-year-olds are vaccinated (22 days, IQR 16, 28) and 90% of over 15-year-olds are vaccinated (24 days, IQR 18, 32).

The actual time to reach 50 infections will depend on the border policy to the extent that some policies result in different distributions of secondary cases from the arriving traveller. The temporal distribution of traveller's infectiousness will also play a role. That said, domestic vaccination levels and whether or not the outbreak was detected in the arriving traveller (allowing the contact tracing system to kick in early) are likely the two primary concerns.

Modelling different public health restrictions to manage COVID-19 as vaccine uptake grows

Purpose

The purpose of this note is to set out key areas of interest for modelling work that will support upcoming decisions about the approach to managing COVID-19 as vaccine coverage grows and border restrictions begin to reduce.

Context

Vaccination reduces (but does not eliminate) the health impacts of COVID and provides more flexibility to manage its effects. If high coverage is achieved, vaccination will enable a wider range of options to control outbreaks of COVID-19, with less frequent need to rely on strict mobility restrictions including 'lockdowns'. However, in New Zealand we don't have any quantitative understanding of the relationship between progress with the vaccine rollout and the 'sets' of public health and social measures that would be sufficient to control a resurgence (i.e. to reduce R0 <1).

In addition, we also do not know how these different approaches compare in terms of economic impacts. For example, even with a highly vaccinated population, some COVID resurgences are likely to need some level of mobility restrictions to manage. Stricter measures will more quickly control an outbreak, while low level restrictions will take longer to control an outbreak. Contact tracing is likely to be more effective at lower numbers of cases, suggesting that larger outbreaks would require more additional restrictions to control. It is also not clear which options have a larger economic cost when the population is highly vaccinated.

Objectives and benefits of this work

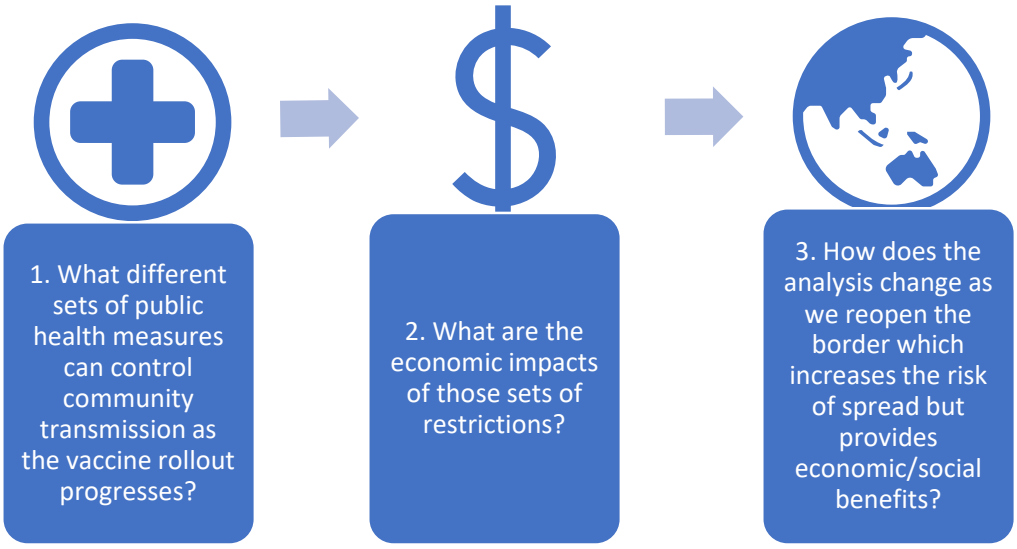
In broad terms we are seeking to answer the question: *what public health measures can effectively manage COVID-19 as the vaccine roll out progresses, and what are the health, border and economic impacts of those options?*

Scenario modelling work on this question would provide the following benefits:

- Support Cabinet decisions on management of the public health response in the later stages of the vaccine rollout and 'Reconnecting NZ' by providing a quantitative assessment of the risks and benefits of different COVID management choices over the medium term.
- Improve public understanding and support for the choices government may take around management of the public health response in the later stages of the vaccine rollout and Reconnecting NZ.
- Enable officials to be in a position advise on policy choices that will have significant public health and economic impacts.

General approach

There are three related questions to this modelling, summarised below. The attached table sets out in more detail the potential questions the modelling could examine, and links with existing work.



The Australian approach

A range of modelling in Australia has taken a scenario-based approach to understanding this relationship. Work by the Doherty Institute and Australian Treasury to support the Australian Government compares the impact of different levels of community vaccination, different management strategies and the bundles of public health measures to control an outbreak.

The strategies examined are broadly either, setting a binding constraint of not overwhelming the contact tracing system, and a (looser) binding constraint of not overwhelming hospital capacity. The former is similar to New Zealand's current 'elimination strategy' and the latter is something closer to a 'flattening the curve' approach where some level of community transmission is always present. A strategy of allowing cases to grow above hospital capacity was not modelled, as it was assumed that the economic and health costs of such a strategy would be too high.

The Australian Treasury then used the Doherty Institute's estimates of the length of time needed to contain the outbreak using bundles of more or less restrictive public health measures to assess the economic costs and compare the approaches. An assumption of 5 outbreaks per quarter is used, in line with Australian experience. They find that even with 70%+ of over 16s vaccinated, it is more cost effective to manage outbreaks by ensuring they do not exceed the capacity of contact tracing system, and with periodic low level restrictions (density and capacity constraints) rather than short but strict lockdowns. Keeping the contact tracing system working as effectively as possible, reduces the need for economically costly public health measures.

This work provides a potential basis and model structure to adapt for New Zealand. There are some key challenges to consider to applying it in a New Zealand context:

- Understanding transmission potential in NZ including how it changes with vaccination and the use of different public health restrictions.
- Considering what would make up a 'baseline' set of public health measures as there is no clear equivalent in NZ.
- Considering the effects on population sub-groups in NZ, as the modelling assumes uniform vaccine coverage and impacts.

Other work in Australia which could provide a model for NZ has also been undertaken by Professor Tony Blakeley (University of Melbourne), https://pursuit.unimelb.edu.au/articles/what-s-the-right-covid-19-risk-to-live-with and the Grattan Institute. https://grattan.edu.au/wp-content/uploads/2021/07/Race-to-80-our-best-shot-at-living-with-COVID-Grattan-Report.pdf

Key data/assumption needs

- Vaccine effectiveness assumptions, including reduction in infection, transmission, symptoms and impact from 'waning'
- Expected vaccination timing and age group structures
- NZ population mixing matrix
- Estimates of Reff across Alert Levels, and potentially with new bundles of interventions
- Estimates of effective capacity of contact tracing system, clinical capacity in hospitals
- Estimates of how the performance contact tracing reduces as more capacity is in use, and the impact on Reff
- Estimates of the frequency of outbreaks

Potential approach to modelling

	Module 1: As a greater proportion of the community is vaccinated, what are our options to manage community transmission?	*Module 2: … What are the economic impacts of these measures?*	*Module 3: How do our choices about reopening the border change these risks and costs?*
Questions to examine through modelling	• As the vaccine roll out progresses, what different sets of public health restrictions would control an outbreak (such that R_0<1) at key points in the vaccination roll out (e.g. 60%, 70%, 80% and 90% of over 12s)? • What are the public health impacts of those choices (e.g. hospitalisations and deaths)? • For what amount of time are these public health restrictions required to contain an outbreak? • How does this change if we rolled out the vaccinations to age groups under 12? • How does this analysis change if our binding constraint is the capacity of the contact tracing and testing system, or the hospital system? • How do different triggers for the use of population-wide restrictions change outcomes? E.g. any cases in the community, when cases are close to breaching contact tracing capacity or hospital system capacity? • What does further investment in the contact tracing and hospital capacity deliver?	• What are the economic impacts of the different bundles of public health restrictions that would control an outbreak at key points in the vaccination roll out? • Which mix of severity and length of public health restrictions at key points in the vaccination roll out creates the lowest economic impact? • What would be the impact of having some level of restrictions in place continuously?	• How do our conclusions in (1) change as we reopen the border in different ways? For example, is there a material difference in public health restrictions needed if a higher or lower risk reopening strategy is chosen? • What are the economic impacts from different border reopening options (both benefits and costs)?
Context and background	Te Pūnaha Matatini's vaccine model paper provides a starting point for this work, setting out the impacts of new COVID cases at different levels of community vaccination.	The Treasury's existing work to assess the impacts of Alert Level restrictions provides a basis for this work. We may need to estimate the economic effects of different 'bundles' of public health restrictions.	Te Pūnaha Matatini have modelled the relative risks of different types of border openings, which will be a key input for this work. There is also modelling under way to inform our understanding of 'traveller

	risk' which would inform our estimates of border risk.

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Cc:	George Whitworth [DPMC]; Gill Hall; xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx ; Patricia Priest; xx@xxxxx.xx.xx ; Harry Nicholls [TSY]
Subject:	Upcoming TPM paper release: vaccination and border testing modelling
Date:	Monday, 8 November 2021 11:05:00 AM
Attachments:	v1.3 Vaccination and Border Testing.docx Summary and interpretation of border testing and isolation paper - clean.docx image002.png

Kia ora kouotou

This is to let you know that TPM plans to release the attached paper tomorrow or Wednesday on their website. This is the final version of the paper we've previously discussed with you that tries to model the risk of border-related outbreaks of COVID-19 from different 'mitigations' imposed on travellers, ranging from vaccination, pre/post arrival testing, and self isolation. It considers these risks in the context of different levels of domestic vaccination.

Our summary (attached) is still relevant for this paper. The main changes since you last saw this are to add some additional sensitivity testing to assess what if the LFT tests are less sensitive than assumed, and if self-isolation adherence is less than assumed. The effects are:

- where the assumed probability of a LFT returning a positive result is lower than the central assumption, the strategies using LFTs still outperform the comparable strategy using PCR tests for reducing the probability of any onward transmission. They are slightly worse than PCR testing at preventing onward transmission that is never detected but the difference is small and could be offset by a PCR test at the end of the self-isolation period.
- where self-isolation only prevents 40% of transmission from asymptomatic arrivals in the community and 60% of transmission from symptomatic arrivals (as opposed to 60% and 80% in the base scenarios), the outcomes worsen over most interventions particularly those involving a 5-day self-isolation period. However, the relative risk reductions of the different policies follow the same qualitative features of the main model results.

Ngā mihi

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I do not work on Thursdays.

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Effect of vaccination, border testing, and quarantine requirements on the risk of COVID-19 in New Zealand: a modelling study

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Executive summary

1. We use a stochastic branching process model to investigate the risk of border-related outbreaks of COVID-19 and strategies to mitigate this risk.
2. Strategies investigated include vaccination requirements, combinations of pre-departure and post-arrival symptom screening and testing using either rapid antigen tests or PCR tests, and post-arrival self-isolation as well as different vaccination rates in the resident population.
3. If vaccination is required as a condition for travel and with high vaccine coverage domestically, reducing the required MIQ stay from 14 days to 7 days results in a small increase in risk, with around 1 in 200 infected travellers expected to transmit the virus into the community.
4. Requiring self-isolation for arrivals means around 1 in 60 infected travellers would transmit the virus into the community. If contact tracing can be used to manage border-related cases, the risk of a significant community outbreak is reduced to around 1 in 150 infected travellers. These results assume the majority of arrivals follow the requirements of isolating at home.
5. Strategies that use regular rapid antigen tests can perform comparably or better than those that use less frequent PCR tests. Strategies that use a combination of rapid antigen and PCR tests at different times may be able to take advantage of the pros of both types of test.
6. The volume of travellers and the risk profile of the countries from which those travellers are coming are also key variables determining the number of infectious individuals arriving at the border. The likely effect of changes in border policy on these variables should also be considered.
7. Uncertainty in how likely individuals are to test positive at different times relative to their ability to spread the virus means that our results should not be treated as exact predictions of absolute risk, but as comparisons of the relative risk reduction provided by different combinations of interventions and at different population vaccine coverage levels.

Abstract

We couple a simple model of quarantine and testing strategies for international travellers with a model for transmission of SARS-CoV-2 in a partly vaccinated population. We use this model to estimate the risk of an infectious traveller causing a community outbreaks under various border control strategies and different levels of vaccine coverage in the population. We find that strategies that rely on home isolation result in significantly higher risk than the current mandatory 14-day stay in government-managed isolation. Nevertheless, combinations of testing and home isolation can still reduce the risk of a community outbreak to around one outbreak per 100 infected travellers. We also find that, under some circumstances, using daily lateral flow tests or a combination of lateral flow tests and polymerase chain reaction (PCR) tests can reduce risk to a comparable or lower level than using PCR tests alone. Combined with controls on the number of travellers from countries with high prevalence of COVID-19, our results allow different options for managing the risk of COVID-19 at the border to be compared. This can be used to inform strategies for relaxing border controls in a phased way, while limiting the risk of community outbreaks as vaccine coverage increases.

Introduction

Since April 2020, New Zealand has pursued a COVID-19 elimination strategy [1] and, through a combination of strict border controls and snap lockdowns when needed, has limited community transmission of SARS-CoV-2 to very low levels. As a result New Zealand has negligible infection-acquired immunity to COVID-19 [2]. Australia has also relied on international border controls and a strong public health response to keep incidence of COVID-19 very low. New Zealand's vaccination programme began in February 2021 and is exclusively using the Pfizer/BioNTech mRNA vaccine. As of mid-September 2021, around 38% of the eligible population (aged over 12 years) are fully vaccinated and an additional 35% have received their first dose [3]. The government aims to offer the vaccine to everyone who is eligible by the end of 2021

During 2021, the Delta variant of SARS-CoV-2 has displaced other variants and become dominant in many countries, including India, the UK and USA – countries with which New Zealand has close travel links. Because of the increased transmissibility of the Delta variant, it is unlikely that countries will be able to reach complete population immunity (i.e. a reproduction number that less than 1 in the absence of any other interventions) via vaccination alone [4, 5]. Other public health measures will be needed to control the virus, although reliance on these will reduce as vaccine coverage increases. These measures may consist of a mixture of border controls designed to reduce the risk of cases being seeded into the population, and community measures designed to enhance surveillance and reduce the potential for transmission.

Recent modelling has shown that the increased transmissibility of the Delta variant has largely nullified the reduction in risk of quarantine breaches gained from vaccination of international travellers and quarantine workers [6]. This means that strong border controls, including limits on travel volume and mandatory government-managed isolation for international arrivals, are still essential to prevent re-introduction of SARS-CoV-2 until the population is protected from the health impacts of COVID-19 by high levels of vaccine coverage. Once vaccination rates are sufficiently high, it is likely that border controls can be gradually relaxed in conjunction with ongoing community public health measures [7]. To do this safely, it will be important to quantify the relative risk of community outbreaks under different sets of mitigation measures for international travellers arriving to at the border. These may include different combinations of government-managed isolation and quarantine (MIQ), self-isolation at home, and pre-departure and post-arrival testing requirements. Between 1 February and 15 September 2021, 83% of New Zealand's border related cases were detected in the first 7 days after

arrival and 75% were detected in the first 5 days. This suggests that a reduced quarantine period of less than 14 days would catch the majority of cases, but other measures such as home isolation and follow-up testing after completion of quarantine testing would be needed. Different sets of requirements could be applied to travellers depending on their risk profile, for example more stringent restrictions for people travelling from countries with high infection rates.

New Zealand has primarily used RT-PCR tests for SARS-CoV-2 testing throughout the pandemic, sometimes known as the gold standard test because of its high sensitivity. Around the world, countries are increasingly complementing PCR testing with lateral flow tests, also known as rapid antigen tests. These have lower sensitivity that PCR tests, particularly in the early and late stages of the infectious period [8, 9]. However, they have the advantage that they return results very quickly (typically within 30 minutes), they are cheap, and they do not require laboratory processing. This means they can be used to test large numbers of people at high frequency (e.g. daily) without stretching laboratory capacity and with fast turnaround of results.

Travel volume is a key determinant of the risk posed by international travel. As a consequence of limited MIQ capacity and citizenship or residence requirements for entry, the volume of international arrivals to New Zealand has been approximately 2% of pre-pandemic levels (with the exception of arrivals from Australia during limited periods of quarantine-free travel). It is important to factor this into risk evaluations because if, for example, a given mitigation provides a 10-fold reduction in the risk per traveller, this will be offset if there is a simultaneous 10-fold increase in travel volume.

In this paper, we use a stochastic model of SARS-CoV-2 transmission and testing to compare the relative reduction in transmission potential from infected travellers under various mitigations and at different levels of vaccine coverage in the resident population. This paper is a policy-oriented application of the model developed by [4] to investigate the potential impact of COVID-19 at different stages in New Zealand's vaccination programme.

The model allows for different effectiveness of isolation under different circumstances, for example MIQ versus self-isolation at home during asymptomatic, pre-symptomatic, symptomatic or confirmed stage of infection [10]. We compare different testing requirements, such as daily lateral flows tests (LFT) or less frequent PCR tests, allowing for the different sensitivity of these tests. The model also includes individual heterogeneity in transmission rates and the probability of returning a positive result if tested. We use the model to simulate community outbreaks seeded by international arrivals

and calculate the probability that such an outbreak meets various pre-defined criteria. The aim is not to identify vaccination targets at which borders can be completely reopened, but rather to support strategies for safe relaxation of travel restrictions by comparing the risk reduction from various policy options.

The modelling approach is similar to that of [11], which estimated the reduction in transmission potential from a range of traveller interventions. The model of [11] modelled individual heterogeneity in viral load trajectories and assumed that the transmission rate and the probability of testing positive are both functions of the viral load. This requires that there is a unique one-to-one mapping between the transmission rate at time t and the probability of testing positive at time t. We found it difficult to reconcile this with the fact that there is significant pre-symptomatic transmission of SARS-CoV-2 and that the likelihood of individuals testing positive in the pre-symptomatic stage appears to be significantly lower than after symptom onset. We therefore take a simpler approach based on an empirically estimated generation time interval and test positivity curve and we investigate the qualitative effects of different forms of heterogeneity in these.

Methods

In this section, we first define the stochastic age-structured model for transmission of SARS-CoV-2. This model includes the effects of vaccination and case-targeted controls (case isolation and contact tracing) once a border-related community outbreak is detected. We then describe the model for different interventions that can be applied to international travellers and how these affect potential transmission from international arrivals into the community. We then describe the model for testing of international travellers, defined in terms of the probability of either a PCR test or a LFT returning a positive test result in terms of the time since infection. Finally, we describe how international travellers, under a given set of border interventions, are used to seed the community transmission model and define the simulation outputs that are calculated.

Age-structured transmission model

We model transmission of SARS-CoV-2 in the community using a stochastic age-structured branching process model in partially vaccinated population [4]. Vaccine allocation is assumed to be static (i.e. we

do not consider simultaneous dynamics of community transmission and an ongoing vaccination programme). We assume that 90% of those over 65 years old are vaccinated and consider different levels of vaccine coverage in the 12-64 year age band (70%, 80%, 90%). For simplicity, we assume all individuals are either fully vaccinated or non-vaccinated (i.e. we do not consider the effect of people who have had a single dose). We assume the vaccine prevents infection in $e_I = 70\%$ of people, and reduces transmission by $e_T = 50\%$ in breakthrough infections. This provides an overall reduction in transmission of 85% [12]. We assume that breakthrough infections and primary infections are equally likely to cause symptomatic disease. This does not preclude breakthrough infections having a lower probability of severe illness or death, although we do not investigate these outcomes in this study.

Infected individuals are categorised as either clinical or subclinical, with the clinical fraction increasing with age [13] – see Table 1. Subclinical individuals are assumed to be $\tau = 50\%$ as infectious as clinical individuals [14]. Clinical individuals are assigned a symptom onset time which is Gamma distributed from exposure time with mean 5.5 days and s.d. 3.3 days [15]. In the absence of interventions, we assume generation times follow a Weibull distribution with mean 5.0 days and s.d. 1.9 days [16]. There is at present conflicting evidence in the literature as to whether the Delta variant of SARS-CoV-2 has a shorter mean generation time or mean incubation period than older variants [17-21]. Generation times in particular are difficult to empirically measure because this requires the infection times of both cases in a transmission pair. If infection times are unavailable but symptom onset dates are known, the serial interval can be used as a proxy for generation time. However, serial interval measurements contain more noise as they depend on both individuals' incubation periods. In addition, for both generation times and serial intervals, realised values are affected by control interventions such as test, trace and isolate measures. To investigate the effect of some of these uncertainties, we perform a sensitivity analysis with a shorter generation time (mean 2.9 days, s.d. 1.9 days) and incubation period (mean 4.4 days, s.d. 1.9 days) [20].

Transmission between age groups is described by a next generation matrix, whose (i, j) entry is defined to be the expected number of secondary infections in age group i caused by a clinical infected individual in age group j in the absence of interventions and given a fully susceptible population:

$$NGM_{i,j} = U u_i C_{j,i}$$

where u_i is the relative susceptibility to infection of age group i [14], C is a contact matrix describing mixing rates between and within age groups [22] [4], and U is a constant representing the intrinsic transmissibility of the virus. The value of U is chosen so that the overall average number of secondary

infections caused by an infected individual is equal to the assumed value of R_0. By default we assume $R_0 = 6.0$ for all simulations, approximately representing the Delta variant of SARS-CoV-2 [19, 20, 23].

All individuals are assigned a gamma distributed random variable Y_l with mean 1 and variance $1/k$, such that the expected number of secondary cases infected by individual l given a fully susceptible population in the absence of interventions (the individual reproduction number) is

$$R_l = (1 - V_l e_T) Y_l \sum_{j=1}^{M} NGM_{j,a_l}$$

where $V_l = 1$ if individual l is vaccinated and zero otherwise, e_T is the vaccine effectiveness against transmission conditional on infection, and a_l is the age group of individual l. The expression above is multiplied by τ if individual l is subclinical. This allows for individual heterogeneity in transmission.

At each timestep of size Δt, infected individuals generate a Poisson distributed number of putative secondary infections with mean:

$$\lambda(t) = R_l \int_{t}^{t+\Delta t} F_l^c(x)\omega(x)\, dx$$

where $F_l^c(x)$ describes the reduction in transmission due to isolation or prevention of travel (see *Border interventions* section below) and $\omega(x)$ is the probability density function for the generation time distribution. Each putative secondary infection is assigned an age-group i with probabilities proportional to the $a_l{}^{\text{th}}$ column of the next-generation matrix (corresponding to the index cases' age-group) and to the vaccinated class with probability v_i. The putative secondary infections in the vaccinated class are then thinned with probability e_I, the assumed vaccine effectiveness against infection. Immunity from prior infection is ignored in the model. This is reasonable because we only consider small community outbreaks and our model is applicable to populations, such as New Zealand and Australia, that have not yet experienced large-scale epidemics

We use a simplified model for case-targeted controls in the community. We assume there are initially no controls in place in the period of time before the outbreak is detected (i.e. before the first positive test result is returned). Outbreaks can be detected either via a positive test result in the infected traveller or by community testing. During the period before the outbreak is detected, we assume that symptomatic individuals in the community are tested with probability $p_{test,pre} = 0.12$. This value is based on the number of people seeking tests as a proportion of the number of people with cold or influenza-like symptoms, estimated using data from FluTracking [24], in a period with no known community transmission of SARS-CoV-2. Once an outbreak has been detected, all existing and

subsequent cases in the outbreak are detected with probability $p_{test,outbreak} = 0.4$, reflecting the surge in testing typically seen after an outbreak is detected. In all cases, there is a delay from symptom onset to the test result being returned that is assumed to be exponentially distributed with mean 4 days. To model the effect of contact tracing, we also assume that, after an outbreak is detected, all infected individuals are traced with probability $p_{trace} = 0.7$ and isolated with a mean delay of 6 days after infection (see Table 1).

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Parameter	Value
Basic reproduction number in the absence of control	$R_0 = 6$
Relative transmission rate for isolated individuals:	
- asymptomatic / pre-symptomatic	$c_{asym} = 0.4$ [0.6 in sensitivity]
- symptomatic unconfirmed	$c_{symp} = 0.2$ [0.4 in sensitivity]
- confirmed cases	$c_{conf} = 0$
- in MIQ	$c_{MIQ} = 0$
Incubation period (gamma distributed)	
- default values	Mean 5.5 days, s.d. 3.3 days
- sensitivity analysis	Mean 4.4 days, s.d. 1.9 days
Generation interval (Weibull distributed)	
- default values	Mean 5.0 days, s.d. 1.9 days
- sensitivity analysis	Mean 2.9 days, s.d. 1.9 days
Relative infectiousness of subclinical individuals	$\tau = 0.5$
Heterogeneity in individual reproduction numbers	$k = 0.5$
Vaccine effectiveness:	
- against infection	$e_I = 0.7$
- against transmission in breakthrough infection	$e_T = 0.5$
Probability of a clinical community case being tested:	
- before an outbreak is first detected	$p_{test,pre} = 0.12$
- after an outbreak is detected	$p_{test,outbreak} = 0.4$
Mean time from symptom onset to test result:	
- before an outbreak is first detected	4 days
- after an outbreak is detected	4 days
Probability of a community case being detected via contact tracing	$p_{trace} = 0.7$
Mean time from infection to quarantine for traced contacts	6 days
Probability of testing positive by PCR on days $[1, \ldots, 21]$ after infection	[0, 0.01, 0.04, 0.33, 0.62, 0.75, 0.79, 0.80, 0.79, 0.77, 0.73, 0.70, 0.66, 0.62, 0.57, 0.52, 0.48, 0.44, 0.40, 0.37, 0.34]
Probability of testing positive by LFT on being PCR positive on days $[4, \ldots, 15]$ after infection: - default values	[0.25, 0.35, 0.66, 0.73, 0.73, 0.70, 0.58, 0.49, 0.42, 0.19, 0.14, 0.03]
- sensitivity analysis	[0.19, 0.27, 0.51, 0.57, 0.57, 0.54, 0.45, 0.38, 0.33, 0.15, 0.11, 0.02]

Age-specific parameters

Age (yrs)	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75+
% of popn	5.98	6.39	6.56	6.17	6.59	7.40	7.44	6.62	6.08	6.41	6.43	6.38	5.77	4.90	4.24	6.64
Pr(clinical) (%)	54.4	55.5	57.7	59.9	62.0	64.0	65.9	67.7	69.5	71.2	72.7	74.2	75.5	76.8	78.0	80.1
Susceptibility*	0.46	0.46	0.45	0.56	0.80	0.93	0.97	0.98	0.94	0.93	0.94	0.97	1.00	0.98	0.90	0.86

228

229 **Table 1.** Parameter values used in the model. *Susceptibility u_i for age group i is stated relative to

230 susceptibility for age 60-64 years.

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Border interventions

We test the effects of a set of interventions depending on policy scenarios (see below) on the expected transmission from an infected traveller. We use $F_l^c(t)$ to denote the transmission rate of individual l at time t under a given intervention c, relative to their unmitigated transmission rate at time t. When $F_l^c(t) = 1$, this means individual l is not quarantined or isolated at time t; when $F_l^c(t) = 0$, this means individual l is fully isolated at time t and cannot transmit the virus. Note that $F_l^c(t)$ is also defined to be zero if individual l has not yet arrived at their destination, or has been prevented from travelling from pre-departure symptom checks or testing. The expected number of secondary cases caused by individual l under interventions c relative to no interventions is given by:

$$\frac{R_l^c}{R_l} = \int_0^\infty F_l^c(t)\omega(t)\,dt$$

where $\omega(t)$ is the probability density function for the generation time distribution.

Interventions can be split into three categories: vaccination requirements, pre-departure tests, and post-arrival restrictions. We consider a few key policies for each category in Table 2. All scenarios assume a baseline level of screening passengers so that 80% of travellers who develop symptoms prior to departure are prevented from travelling, independent of any testing requirements.

Vaccination	Pre-departure	Post-arrival
Fully vaccinated	No test	No requirements
Not vaccinated	PCR on day -3	PCR test on days 0 and 4
	LFT on day -1	Daily LFT for 5 days
		5 day self-isolation with PCR test on days 0 and 4
		5 day self-isolation with daily LFT
		7 days MIQ with PCR test on day 5
		14 days MIQ with PCR test on days 3 and 12

Table 2. Overview of key border interventions considered for international travellers. Interventions can be categorised as vaccination requirements, pre-departure testing requirements and post-arrival interventions.

Self-isolation after arrival can occur for any one of four reasons:

1. Due to a requirement to self-isolate while asymptomatic, assumed to reduce transmission to $F_l^c(t) = c_{asymp}$.
2. Due to onset of symptoms, assumed to reduce transmission to $F_l^c(t) = c_{symp}$, regardless of the border policy. Isolation is assumed to begin on the day following symptom onset. This might represent a situation where recent arrivals are contacted by public health teams to encourage monitoring of symptoms.
3. Due to return of a positive test, assumed to reduce transmission to $F_l^c(t) = c_{conf}$, regardless of the border policy. Isolation is assumed to begin on the day following the return of a positive result.
4. Due to a requirement to enter MIQ. For simplicity, we assume there is no risk of transmission between travellers in MIQ facilities ($F_l^c(t) = c_{MIQ} = 0$). Transmission between travellers in MIQ facilities is known to have occurred [25, 26], but this risk is likely to be much smaller than the risk of transmission from individuals in self-isolation at home.

Individuals isolate with the effectiveness of the strongest measure that applies at time t. In all scenarios, we assume that self-isolation prevents 100% of transmission from confirmed cases ($F_l^c(t) = c_{conf}$). Self-reported adherence to requested quarantine measures in a Norwegian study was 71% of those with COVID-19-compaible symptoms and 28% of those without [10]. In the base scenario, we assume that self-isolation at time t prevents 60% of transmission for travellers who are asymptomatic or pre-symptomatic at time t ($c_{asymp} = 0.4$) and prevents 80% of transmission for travellers who are symptomatic but have not yet received a positive test result at time$t$ ($c_{symp} = 0.2$). We also perform a sensitivity analysis where self-isolation is less effective than in the base scenario ($c_{asymp} = 0.6$ and $c_{symp} = 0.4$).

This formulation assumes that all isolated individuals transmit at a reduced rate c. However, we expect average model outputs to be very similar if we instead assumed that a fraction c of isolated individuals transmit at the same rate as a non-isolated individual and a fraction $1 - c$ do not transmit at all [11]. Individuals that develop symptoms after arrival seek a test with probability 80%. This test is assumed to be a PCR test taken with an exponentially distributed delay with mean 2 days after symptom onset and the result is returned the following day. If the individual is scheduled for any kind of test on the same day, they do not take the additional test.

Testing

Travellers are assigned curves representing the probability of testing positive as a function of time since exposure. For RT-PCR tests we use data from [27], with a peak probability of testing positive of 81% eight days after infection (Figure 1). We construct a similar function for the probability of testing positive by LFT based on data from [28]. These results showed that 24 out of 25 individuals tested returned a positive LFT on the day after first positive culture of the virus from a nasal swab. However, real-world test performance is likely to be lower than in a controlled laboratory study with a small sample size. We therefore scaled the data from [28] so that the peak probability of testing positive was 73% (which is 90% of the PCR peak). We assumed that the peak occurs at the same time as the peak for the PCR test, i.e. eight days after infection, with lower probabilities either side of the peak (see Figure 1). In addition, we assume that it is not possible to test negative by PCR and positive by LFT on the same day. To generate an LFT result, we therefore simulate the result of a putative PCR test where probability of a positive result is as shown by the blue curve in Fig. 1. If the putative PCR result is negative, we assume the LFT result is also negative. If the putative PCR result is positive, we assume the LFT result is positive with probability $P(LFT^+|PCR^+) = P^+_{LFT}(t)/P^+_{PCR}(t)$, which is the ratio of the red curve to the blue curve in Fig. 1.

Note that, although the peak sensitivity of the LFT is assumed to be 90% of the peak sensitivity of a PCR test, the overall sensitivity of the LFT is lower than this because of the faster decay away from the peak (Figure 1). Under the model assumptions, a PCR test taken on a random day in the one week or two weeks following symptom onset will detect 77% or 66% of infected individuals respectively, relative to 60% or 33% of infected individuals respectively for a LFT. Although precise characterisation of time-dependent test performance is difficult, this is broadly consistent with results showing that LFTs detected between 40% and 80% of PCR-positive cases [29, 30] [31] [9, 32]. However, we also investigate a sensitivity analysis in which the peak sensitivity of the LFT is only 57%, which is 70% of the peak sensitivity of a PCR test (see Table 1 for time-dependent probabilities).

The probability of testing positive is assumed to be the same for subclinical and clinical individuals. Conditional on being infected, the probability of testing positive is assumed to be the same for vaccinated as for non-vaccinated individuals.

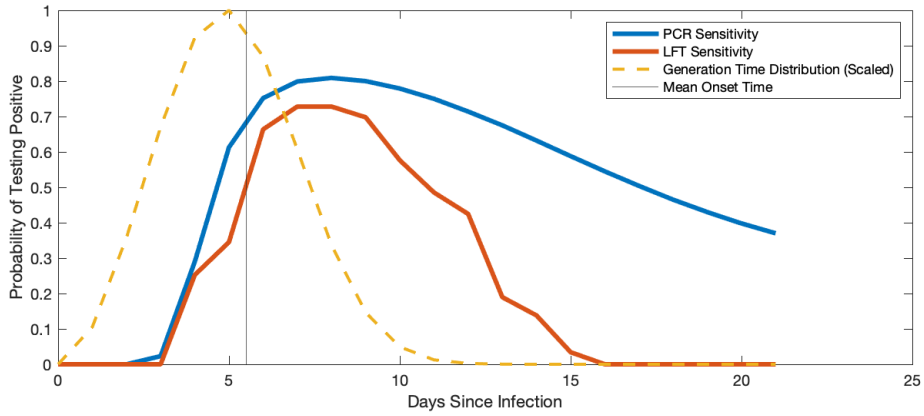

Figure 1. Assumed probability of testing positive as a function of time since infection for PCR (blue) and LFT (red). Dashed curve shows the scaled generation time distribution, showing that a significant amount of transmission can occur prior to test positivity.

It is clear from Figure 1 that, under these assumptions, a significant amount of transmission occurs before the infected person has a high probability of testing positive. This may seem pessimistic but it is consistent with the fact that pre-symptomatic transmission of SARS-CoV-2 is known to be common and with empirical data showing that the probability of testing positive prior to symptom onset is much smaller than after symptom onset [27]. We also perform a sensitivity analysis to investigate the consequences of shifting the probability curves in Figure 1 to the left by 2 days.

Model outputs

For each set of interventions c, we run $N = 100{,}000$ simulations, each initialised with one infected traveller. The traveller is assigned an age-group with a frequency proportional to the New Zealand age-structure, an infection time uniformly randomly distributed in the 14 days prior to arrival, and a clinical status that depends on age. The simulation returns the transmission potential of the infected traveller (R_i^c) and a list of any infections in the community. From these simulations, we report three model outputs defined as follows.

Output (1) is the transmission potential of infected travellers under interventions c relative to the transmission potential in the absence of interventions. This is defined as $\overline{R_i^c}/\overline{R_i^0}$ where the bar denotes the mean of N simulations.

Output (2) is the proportion of simulations meeting each of the following four criteria: (i) the infected traveller causes any onward transmission in the community; (ii) the infected traveller causes onward transmission in the community and is never detected; (iii) the infected traveller leads to an outbreak that reaches 5 infections; (iv) the infected traveller leads to a large outbreak that reaches 50 infections. Note that because the reproduction number is significantly greater than 1, even at the highest vaccine coverage level considered (90% of over-12s), outbreaks that reach 50 infections are almost certain to continue to grow indefinitely until control measures are introduced (or there is a build-up of population immunity). The size of an outbreak that would be concerning varies depending on context. The criteria of 50 infections is arbitrary, but is a convenient point at which to terminate simulations and indicates that community transmission has become established and stochastic extinction is unlikely.

Finally, output (3) is the number of infected travellers who would be expected to result in one large outbreak (that reaches 50 cases from one traveller). If, for example, an average of one outbreak per month is tolerable, then this is the number of infected travellers who would be tolerated per month. This is equal to the reciprocal of the probability that an infected traveller starts a large outbreak.

Model extension: individual heterogeneity in probability of testing positive

In the base model described above, we ignore heterogeneity between individuals in the probability of testing positive at a given time. In reality, there may be variability in the timing, magnitude and duration of the probability of testing positive, and these may be correlated with individual infectiousness. This could affect the performance of different risk mitigation strategies. Explicitly modelling these heterogeneities and correlations would require data on the probability of testing positive and infectiousness, stratified by individual and time. In the absence of detailed data on this, we consider a simplified model for individual heterogeneity.

The base model includes heterogeneity in transmission, via the individual parameter Y with mean 1 and variance $1/k$. Two key contributors to this heterogeneity are variability in contact rates (which is not correlated with probability of testing positive) and variability in viral shedding (which is likely to be correlated with probability of testing positive). We model these two contributions by writing $Y = Y_1 Y_2$ where Y_1 and Y_2 are independent random variables each with mean 1. Conceptually, Y_1 quantifies behavioural factors that affect transmission (i.e. contact rates during the infectious period), whereas

Y_2 is related to biological characteristics of the viral infection (e.g. viral load) in a particular individual. In the base model with no heterogeneity in probability of testing positive, $Var(Y_2) = 0$ and heterogeneity in transmission is entirely due to individual differences in contact rates. Fixing $Var(Y)$ and increasing $Var(Y_2)$ increases the correlation amongst individuals between transmission and probability of testing positive.

To implement this model, we assume $Y_1$is gamma distributed with mean 1 and variance $1/k^*$, and Y_2 is normally distributed with mean 1 and varaicne σ^2 truncated to non-negative values. If we set $k^* = k(1+\sigma^2)/(1-k\sigma^2)$, then provided σ^2 is sufficiently small, the product Y_1Y_2 is approximately gamma distributed with mean 1 and variance $1/k$, as for the base model. We assume that the odds of testing positive are proportional to Y_2 and so we set the probability that a test on individual l at time t returns a positive result to be $\frac{y_{2,l}P^+(t)}{1-(1-y_{2,l})P^+(t)}$, where $y_{2,l}$ is the value of the random variable Y_2 for individual l and $P^+(t)$ is the relevant test positivity curve for either PCR or LFT shown in Figure 1.

Results

Relative transmission potential

The relative transmission potential measures the reduction in the expected number of secondary cases per infected traveller as a result of a given border intervention c. By construction, the relative transmission potential measures of the effectiveness of a given border intervention in reducing risk, independent of the assumed value of R_0 and of the level of vaccine coverage in the domestic population. For example, a set of interventions for which the relative transmission potential is 0.6 means that an individual infected traveller under this intervention is on average 60% as risky as they would be with no interventions. Figure 2 shows the effect of the interventions considered on the average transmission potential of an infected traveller over time, relative to the unmitigated potential on day 0. The effect of scheduled tests can be seen as an instantaneous reduction in transmission potential as cases are detected are put into strict isolation. The overall transmission potential under a given intervention is proportional to the area under the corresponding curve shown in Figure 2.

Table 3 shows the relative transmission potential of an average infected traveller under a given border policy. All results are relative to the same baseline, representing the transmission potential of a non-vaccinated traveller that faces no interventions other than a pre-departure symptom check.

Conditional on being infected, a vaccinated individual is assumed to be approximately 50% as infectious as a non-vaccinated individual (Table 1). Vaccinated individuals are less likely to be infected than a non-vaccinated person in the first place. However, we do not attempt to model the epidemic dynamics in the traveller's country of origin so the results do not capture this effect.

The introduction of regular post-arrival symptom checks and isolation for symptomatic travellers (assumed to be 80% effective from the day following symptom onset) reduces the transmission potential to 78% of the baseline (unmitigated) transmission potential for non-vaccinated travellers and 39% for vaccinated travellers.

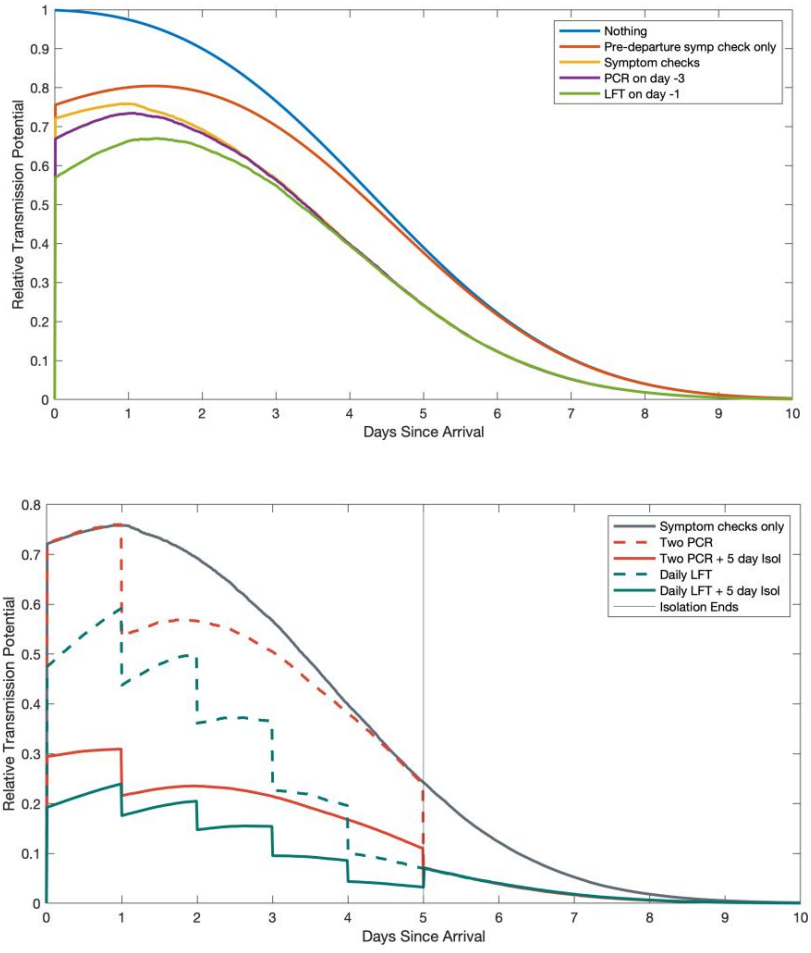

Figure 2. Average transmission potential of an infected traveller as a function of time since arrival under a given set of interventions, relative to the transmission potential of an infected traveller on day 0 with no mitigation.

The addition of a pre-departure testing requirement provides a relatively small additional reduction in transmission potential (for vaccinated travellers from 39% with no pre-departure testing to 38% for PCR on day -3 or 36% for LFT on day -1). Although pre-departure testing and symptom checks screen out a significant fraction of infected travellers (approximately 34% for symptom-checks only, 54% with the addition of either test), many of these travellers would have been towards the end of their infectious period by the time they arrived at their destination. This explains why the reduction in transmission potential is relatively modest. The small difference between the effect of a PCR tests on day -3 and a LFT test on day -1 suggests the reduced sensitivity of the LFT is roughly offset by the fact it can be done closer to the time of departure.

Of the post-arrival testing strategies, a daily LFT for 5 days is more effective (reducing transmission potential from 39% to 22% for vaccinated travellers) than PCR tests on day 0 and day 4 (39% to 33%). This shows that, under the assumed test characteristics, the lower sensitivity of LFT tests is outweighed by the increased frequency of testing and faster return of results.

Adding a requirement for five days self-isolation after arrival further reduces transmission potential (from 33% to 15% with the PCR testing strategy and from 22% to 10% with the LFT strategy, for vaccinated travellers). Finally, a seven-day stay in MIQ with two PCR tests reduces transmission potential to approximately 0.2% for vaccinated travellers, and a fourteen-day stay in MIQ with two PCR tests reduces the transmission potential to a negligible level. Note that the model does not attempt to include the risk of transmission within MIQ facilities.

Risk of onward transmission

Table 4 shows the probability that an infected traveller leads to any onward transmission in the community. These risks all decrease as the vaccine coverage in the resident population increases. The results are presented for both vaccinated and non-vaccinated travellers in the tables, although we focus on vaccinated travellers in the results described below.

When only pre-departure symptom checks are included, there is a 32% chance that an infected vaccinated traveller leads to onward transmission (whether detected or undetected) for a fully susceptible population (i.e. no vaccine coverage). This decreases to 27% when 90% of the domestic population aged 12 years or over is vaccinated. Note that population vaccine coverage only reduces

the risk of onward transmission due to the infection blocking aspect of the vaccine, which is assumed to have an effectiveness of $e_I = 70\%$. The risk of an outbreak to a certain size (see Tables 6 and 7 described below) is further reduced by the transmission-reducing aspect of the vaccine. The addition of post-arrival symptom checks results in a modest reduction in the probability of onward transmission (31% without domestic vaccination, decreasing to 25% at 90% coverage of over-12s). This decreases to 28%/24% with the addition of a pre-departure PCR test, or to 26%/21% with the addition of a pre-departure LFT test.

Consistent with the results in Table 3, daily LFTs for 5 days after arrival make the risk of onward transmission smaller (21% with no vaccine coverage, dropping to 17% at 90% coverage of over-12s) than PCR tests on day 0 and day 4 (29% with no vaccine coverage dropping to 23% at 90% coverage of over-12s). When five days of self-isolation are required, we again find that daily LFT tests perform better at preventing any onward transmission (14% for LFT compared to 19% for PCR with no vaccine coverage). The probability of onward transmission following a 7-day MIQ stay is between 0.5% and 1% depending on vaccine coverage in the population.

The LFT-based strategies also performs better than the corresponding PCR strategies at reducing the probability that an infected traveller transmits the virus without ever being detected by testing (Table 5). This is important because detecting a travel-related case, even after they have passed the virus on in the community, allows contact tracing to begin which may be able to extinguish the outbreak in its early stages. However, the differences between the LFT and PCR strategies are relatively small because, although daily LFTs detect a reasonably high proportion of cases before they can transmit, PCR tests are more sensitive in the later stages of the infection. Motivated by this, we also calculated the probability of undetected onward transmission under alternative strategies where travellers take daily LFTs on days 0 to 3 followed by a PCR test on day 4. We found that these strategies performed comparably to the LFT-only strategies at preventing onward transmission, but outperformed both the LFT-only and PCR-only strategies at preventing undetected onward transmission (Supplementary Table 1). For example, the probability of undetected onward transmission from an infected vaccinated traveller into a non-vaccinated population is 1.8% in the mixed testing strategy compared to 2.8% for LFT-only and 4.0% for PCR-only.

Risk of community outbreaks

Tables 6 and 7 show the probability that an infected traveller starts an outbreak that reaches at least 5 cases and at least 50 cases respectively. Comparing Tables 6 and 7 reveals that, in a non-vaccinated population, most outbreaks that reach 5 cases also go on to reach 50 cases, as the respective probabilities are very similar. As vaccine coverage increases, the probability of an outbreak reaching 50 cases drops below the probability of reaching 5 cases. This shows that, in a highly vaccinated population, outbreaks may cause a few cases but increasingly fail to establish and take off. These scenarios assume effective contact tracing is implemented once an outbreak is detected (either via a positive test result in the traveller who triggered the outbreak or via symptomatic community testing), so while vaccination levels are low, additional controls would almost always be necessary to control an outbreak.

High levels of community vaccine coverage decrease the risk that a vaccinated traveller with only pre-departure symptom checks starts a large outbreak from 16% with no vaccination, to 4.5% with 90% of over 12-year-olds vaccinated. Introducing a pre-departure LFT and post-arrival symptom checks decreases this to 2.8%. Further introducing a PCR test on day 0 and 4 after arrival takes this to 1.8% while daily LFT for 5 days after arrival takes this to 1.2%. Requiring 5 days of self-isolation reduces the risk to 0.9% with the PCR testing strategy or 0.6% with the LFT testing strategy. A 7-day stay in MIQ reduces the risk to a much lower level (<0.05%).

These results can also be interpreted in terms of the number of infected travellers that are expected to lead to one large outbreak (Table 8). Aside from those involving MIQ, the only scenario that consistently tolerates more than 80 infected travellers per large outbreak is 5 day self-isolation with daily LFTs and at least 80% domestic vaccine coverage, or 5 day self-isolation with two PCR tests and 90% vaccine coverage. Aside from MIQ, there is no scenario where domestic vaccine coverage is below 80% of over 12-year-olds and more than 80 infected travellers can be allowed to enter without a large outbreak being expected.

Sensitivity analyses

Results for the model with individual heterogeneity in the probability of testing positive (Supplementary Tables 2-4) show that this appears to be a relatively small part of the overall

stochasticity of the simulation results. Including heterogeneity has very little effect on the average relative transmission potential, but slightly increases the risk of undetected onward transmission relative to the homogeneous model. This is because more infected individuals will be missed, even when tested on multiple occasions. Further modelling work and better data on test characteristics are needed to more completely understand the sensitivity of the results to heterogeneity, but at this stage it appears to be a relatively small effect.

If individuals tend to test positive earlier in the course of their infection (shifting the curves in Figure 1 to the left by 2 days), this decreases all measures of risk (Supplementary Tables 5-7), particularly for interventions involving with daily LFT testing. Conversely, if the generation time and incubation period are shorter (mean 2.9 days and 4.4 days respectively), the relative transmission potential is higher (Supplementary Table 8). However, this is not a good basis for comparison with the default parameter values (see Table 1) because the baseline (unmitigated) transmission potential depends on generation time assumptions. The risk of onward transmission (Supplementary Tables 9-10) is a better basis for comparison and this is lower for the short generation time scenario. This is because most transmission occurs in the first few days following infection, so testing and short isolation periods after arrival are more effective at preventing contact with the community during the infectious period.

In a sensitivity analysis where the assumed probability of a LFT returning a positive result is lower (see Table 1), the strategies using LFTs still outperform the comparable strategy using PCR tests for reducing the probability of any onward transmission (Supplementary Tables S11-S12). They are slightly worse than PCR testing at preventing onward transmission that is never detected (Supplementary Tables S13), though the difference is small and could be offset by a PCR test at the end of the self-isolation period (see above). Finally, we performed a sensitivity analysis where self-isolation only prevents 40% of transmission from pre-symptomatic or asymptomatic arrivals in the community during and 60% of transmission from symptomatic arrivals (Supplementary Tables S13-S15), as opposed to 60% and 80% in the base scenarios). As expected, the risk metrics are higher under most interventions particularly those involving a 5-day self-isolation period. However, the relative risk reductions of the different policies follow the same qualitative features described above.

Discussion

We have modelled the effect of different border controls on the risk of international travellers infected with SARS-CoV-2 transmitting the virus and triggering community outbreaks. Potential border measures include a requirement for travellers to be vaccinated, different combinations of pre-departure testing and post-arrival testing and quarantine. We investigated outcomes at different levels of vaccine coverage in the domestic population.

Our results should be interpreted as estimates of the relative effectiveness of alternative mitigation strategies, rather than absolute predictions of risk. For example, the model estimates that pre-departure tests alone have a relatively small impact on the risk of a community outbreak. Adding post-arrival testing requirements provides a larger benefit and can cut the risk by around 50% relative to no testing. A further requirement for 5 days of self-isolation at home can cut the risk to around one third of the risk without mitigations. This result assumes that self-isolation is 40% effective in reducing transmission for asymptomatic or pre-symptomatic individuals and 80% effective for symptomatic individuals. The model results also clearly show the progressive reduction in risk as vaccine coverage in the domestic population increases: achieving 90% vaccine coverage amongst over-12-year-olds cuts the risk of a community outbreak by roughly a factor of 3.

Our results describe the risks per infected would-be traveller. The other key determinant of overall risk is the number of infected travellers, which is a product of the prevalence of infection amongst travellers and the travel volume. The latter variable is crucial because, while current travel volume is approximately 2,500 arrivals to New Zealand per week, this could increase substantially with the relaxation of travel eligibility and quarantine requirements. For example, a hypothetical scenario with 50,000 arrivals per week (i.e. around 50% of pre-pandemic travel volume) and a prevalence of 0.15 infections per 1000 travellers would mean around 7.5 infected arrivals per week. Under the more optimistic scenarios with high vaccine coverage and 5-day self-isolation and testing requirements, the model estimates the risk of a community outbreak to be in the region of 1-2% per infected traveller. This would translate to around one new community outbreak every 6-12 weeks.

If vaccine coverage is sufficiently high, the majority of these outbreaks may be stamped out with targeted measures like intensive community testing and contact tracing [4]. However, this would likely require significantly higher capacity than has been used in previous outbreaks in New Zealand. In addition, some outbreaks would likely require broader interventions or even localised lockdowns,

particularly if they affected population groups with relative low vaccine coverage or high contact rates. This suggests a staged approach to relaxing travel restrictions with a gradual as opposed to a sudden increase in travel volume, allowing case management and outbreak control systems to be tested.

The over-dispersed nature of SARS-CoV-2 transmission implies many infected people do not transmit the virus, or only infect one or two others, whereas a small minority of cases can infect a large number of other people. This means that, although the probability of an individual transmitting the virus may be low, the ones who do transmit can lead to outbreaks that grow faster than an average would suggest.

The assumed reduction in transmission from individuals in self-isolation at home does not capture any specific effects, such as the increased relative likelihood of transmission to household contacts. Policies such as requiring all household contacts of self-isolating travellers to be vaccinated or mandating the collection of contact tracing information would further reduce risk. However, the effectiveness of home isolation is largely untested in the New Zealand context. Analysis of contact tracing data from March 2021 suggested that the introduction of a self-isolation requirement for international arrivals reduced transmission by 35% [33], although this estimate was based on a small dataset that may not be representative of future cohorts of travellers.

Lateral flow tests have not been widely used in New Zealand previously. Our results suggest that there could be a place for LFTs as part of a comprehensive border management strategy. Although they are less sensitive than PCR tests, particularly in the early or late stages of infection [8], this can be compensated for by the fact that they can be used more frequently and provide results rapidly without the need for laboratory processing. For example, the model estimates that daily testing of arrivals with LFTs for 5 days provides a bigger risk reduction than a PCR test on days 0 and 4. Sensitivity analysis indicates that the magnitude of this advantage depends on factors such as individual heterogeneity in viral loads and the temporal correlation between infectiousness and likelihood of testing positive. Daily LFT testing combined with a PCR test on the last day could combine the benefits of regular testing in preventing transmission with the sensitivity of a PCR test for detecting cases that may have been missed by LFT. Trialling LFTs these alongside PCR tests in MIQ facilities and frontline border workers would allow for the collection of valuable real-world data to evaluate their sensitivity at different times relative to symptom onset.

We have assumed that vaccinated and non-vaccinated individuals, if infected, have the same probability of developing symptoms of COVID-19. If in reality vaccinated infected people may be less likely to develop symptoms, the effectiveness of post-arrival symptom checks and symptom-triggered testing in vaccinated travellers will be less than in the results shown here. However, this reduced effectiveness may be offset if likelihood of developing symptoms is correlated with infectiousness. Further work is needed to investigate this.

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Post-arrival	Pre-depart	Non-vacc traveller	Vacc traveller
None	Symp check only	100%	50%
Regular symptom checks	No test	78%	39%
	PCR on day -3	76%	38%
	LFT on day -1	73%	36%
PCR on days 0 & 4	No test	66%	33%
	PCR on day -3	66%	33%
	LFT on day -1	63%	32%
Daily LFT for 5 days	No test	45%	22%
	PCR on day -3	44%	22%
	LFT on day -1	43%	22%
5 day isolation + PCR on days 0 & 4	No test	29%	15%
	PCR on day -3	29%	15%
	LFT on day -1	28%	14%
5 day isolation + daily LFT	No test	20%	10%
	PCR on day -3	20%	10%
	LFT on day -1	19%	10%
7 day MIQ + PCR on days 0 & 4	No test	0.36%	0.18%
	PCR on day -3	0.35%	0.18%
	LFT on day -1	0.36%	0.18%
14 day MIQ + PCR on days 3 & 12	No test	0.0%	0.0%
	PCR on day -3	0.0%	0.0%
	LFT on day -1	0.0%	0.0%

Table 3. Average remaining transmission potential of infected travellers under various border controls. All scenarios assume pre-departures symptom checks, regular post-arrival symptom checks, and symptom-triggered testing are implemented, with the exception of the first row. Results are from 100,000 independent simulations representing 100,000 infected travellers.

		Non-vaccinated traveller				Vaccinated traveller			
Post-arrival	**Pre-depart**	**0%**	**70%**	**80%**	**90%**	**0%**	**70%**	**80%**	**90%**
None	Symp check only	36%	33%	32%	31%	32%	28%	28%	27%
Regular symptom checks	No test	35%	31%	30%	29%	31%	26%	26%	25%
	PCR on day -3	32%	29%	28%	28%	28%	25%	24%	24%
	LFT on day -1	29%	26%	26%	25%	26%	23%	22%	21%
PCR on days 0 & 4	No test	33%	29%	29%	28%	29%	25%	24%	23%
	PCR on day -3	30%	27%	27%	26%	27%	23%	23%	22%
	LFT on day -1	28%	25%	24%	24%	25%	21%	21%	20%
Daily LFT for 5 days	No test	24%	22%	21%	20%	21%	18%	18%	17%
	PCR on day -3	23%	21%	20%	20%	21%	18%	17%	17%
	LFT on day -1	22%	20%	19%	19%	20%	17%	16%	16%
5 day isolation + PCR on days 0 & 4	No test	28%	24%	23%	22%	23%	19%	18%	17%
	PCR on day -3	26%	23%	22%	21%	22%	18%	17%	17%
	LFT on day -1	24%	21%	20%	19%	20%	17%	16%	15%
5 day isolation + daily LFT	No test	20%	17%	17%	16%	17%	14%	13%	13%
	PCR on day -3	20%	17%	17%	16%	17%	14%	13%	12%
	LFT on day -1	19%	16%	16%	15%	16%	13%	12%	12%
7 day MIQ + PCR on days 0 & 4	No test	1.32%	0.97%	0.91%	0.84%	0.92%	0.63%	0.58%	0.53%
	PCR on day -3	1.32%	0.97%	0.90%	0.83%	0.92%	0.63%	0.58%	0.53%
	LFT on day -1	1.33%	0.97%	0.91%	0.84%	0.93%	0.64%	0.59%	0.54%
14 day MIQ + PCR on days 3 & 12	No test	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on day -3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on day -1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4. Probability that an infected traveller leads to any onward transmission. Columns headings 0%, 70%, 80%, and 90% refer to the percentage of 12-to-64-year-olds that are vaccinated in the community; all scenarios (except 0% coverage) assume 90% of over 65-year-olds are fully vaccinated. Results are from 100,000 independent simulations representing 100,000 infected travellers.

		Non-vaccinated traveller				Vaccinated traveller			
Post-arrival	**Pre-depart**	**0%**	**70%**	**80%**	**90%**	**0%**	**70%**	**80%**	**90%**
None	Symp check only	36%	33%	32%	31%	32%	28%	28%	27%
Regular symptom checks	No test	24%	21%	21%	20%	21%	18%	18%	17%
	PCR on day -3	21%	19%	19%	19%	19%	17%	16%	16%
	LFT on day -1	19%	18%	17%	17%	17%	15%	15%	14%
PCR on days 0 & 4	No test	4.4%	4.0%	4.0%	3.9%	4.0%	3.5%	3.4%	3.3%
	PCR on day -3	4.2%	3.9%	3.8%	3.7%	3.8%	3.4%	3.4%	3.3%
	LFT on day -1	4.0%	3.7%	3.6%	3.6%	3.7%	3.3%	3.2%	3.1%
Daily LFT for 5 days	No test	3.1%	2.9%	2.8%	2.8%	2.8%	2.5%	2.5%	2.4%
	PCR on day -3	3.1%	2.8%	2.8%	2.7%	2.8%	2.5%	2.4%	2.4%
	LFT on day -1	3.0%	2.8%	2.7%	2.7%	2.8%	2.5%	2.4%	2.4%
5 day isolation + PCR on days 0 & 4	No test	3.9%	3.5%	3.4%	3.3%	3.4%	2.9%	2.8%	2.7%
	PCR on day -3	3.9%	3.5%	3.4%	3.3%	3.4%	2.9%	2.8%	2.7%
	LFT on day -1	3.7%	3.3%	3.3%	3.2%	3.2%	2.8%	2.7%	2.6%
5 day isolation + daily LFT	No test	2.8%	2.5%	2.5%	2.4%	2.5%	2.2%	2.1%	2.1%
	PCR on day -3	2.8%	2.5%	2.5%	2.4%	2.5%	2.2%	2.1%	2.0%
	LFT on day -1	2.8%	2.5%	2.5%	2.4%	2.4%	2.1%	2.1%	2.0%
7 day MIQ + PCR on days 0 & 4	No test	1.14%	0.83%	0.78%	0.72%	0.78%	0.53%	0.49%	0.45%
	PCR on day -3	1.13%	0.82%	0.77%	0.71%	0.77%	0.53%	0.49%	0.44%
	LFT on day -1	1.13%	0.82%	0.77%	0.71%	0.79%	0.54%	0.50%	0.45%
14 day MIQ + PCR on days 3 & 12	No test	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on day -3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on day -1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 5. Probability that an infected traveller: (i) leads to any onward transmission, and (ii) is not detected by testing. Columns headings 0%, 70%, 80%, and 90% refer to the percentage of 12-to-64-year-olds that are vaccinated in the community; all scenarios (except 0% coverage) assume 90% of over 65-year-olds are fully vaccinated. Results are from 100,000 independent simulations representing 100,000 infected travellers.

Post-arrival	Pre-depart	0%	70%	80%	90%
None	Symp check only	16.7%	10.1%	8.8%	7.4%
Regular symptom checks	No test	14.5%	8.4%	7.3%	6.0%
	PCR on day -3	14.3%	8.2%	7.2%	5.9%
	LFT on day -1	13.1%	7.8%	6.9%	5.6%
PCR on days 0 & 4	No test	12.7%	7.0%	6.0%	4.9%
	PCR on day -3	12.3%	6.9%	6.0%	4.9%
	LFT on day -1	11.7%	6.6%	5.7%	4.6%
Daily LFT for 5 days	No test	9.2%	4.8%	4.2%	3.3%
	PCR on day -3	8.9%	4.9%	4.1%	3.3%
	LFT on day -1	8.7%	4.8%	4.0%	3.2%
5 day isolation + PCR on days 0 & 4	No test	7.8%	3.7%	3.1%	2.4%
	PCR on day -3	7.6%	3.8%	3.0%	2.4%
	LFT on day -1	7.4%	3.5%	2.8%	2.4%
5 day isolation + daily LFT	No test	5.5%	2.6%	2.1%	1.7%
	PCR on day -3	5.5%	2.5%	2.1%	1.6%
	LFT on day -1	5.2%	2.5%	2.0%	1.6%
7 day MIQ + PCR on days 0 & 4	No test	0.16%	0.06%	0.05%	0.03%
	PCR on day -3	0.16%	0.07%	0.05%	0.04%
	LFT on day -1	0.16%	0.05%	0.04%	0.04%
14 day MIQ + PCR on days 3 & 12	No test	0.0%	0.0%	0.0%	0.0%
	PCR on day -3	0.0%	0.0%	0.0%	0.0%
	LFT on day -1	0.0%	0.0%	0.0%	0.0%

675

676 **Table 6.** Probability of an infected vaccinated traveller starting an outbreak leading to at least 5
677 infections. Columns headings 0%, 70%, 80%, and 90% refer to the percentage of 12-to-64-year-olds
678 that are vaccinated in the community; all scenarios (except 0% coverage) assume 90% of over 65-year-
679 olds are fully vaccinated. Results are from 100,000 independent simulations representing 100,000
680 infected travellers.

681

Post-arrival	Pre-depart	0%	70%	80%	90%
None	Symp check only	16.4%	8.7%	6.7%	4.5%
Regular symptom checks	No test	14.2%	6.7%	5.0%	3.1%
	PCR on day -3	13.9%	6.5%	4.9%	3.1%
	LFT on day -1	12.8%	6.2%	4.7%	2.8%
PCR on days 0 & 4	No test	12.1%	4.9%	3.4%	1.9%
	PCR on day -3	11.7%	4.8%	3.3%	1.9%
	LFT on day -1	11.2%	4.6%	3.2%	1.8%
Daily LFT for 5 days	No test	8.7%	3.3%	2.3%	1.3%
	PCR on day -3	8.5%	3.4%	2.3%	1.2%
	LFT on day -1	8.2%	3.3%	2.2%	1.2%
5 day isolation + PCR on days 0 & 4	No test	7.4%	2.5%	1.7%	0.9%
	PCR on day -3	7.3%	2.6%	1.6%	0.9%
	LFT on day -1	7.0%	2.4%	1.5%	0.9%
5 day isolation + daily LFT	No test	5.2%	1.7%	1.1%	0.6%
	PCR on day -3	5.2%	1.7%	1.1%	0.6%
	LFT on day -1	4.9%	1.7%	1.0%	0.6%
7 day MIQ + PCR on days 0 & 4	No test	0.16%	0.06%	0.04%	0.02%
	PCR on day -3	0.16%	0.06%	0.04%	0.02%
	LFT on day -1	0.16%	0.04%	0.03%	0.02%
14 day MIQ + PCR on days 3 & 12	No test	0.0%	0.0%	0.0%	0.0%
	PCR on day -3	0.0%	0.0%	0.0%	0.0%
	LFT on day -1	0.0%	0.0%	0.0%	0.0%

Table 7. Probability of an infected vaccinated traveller starting a large outbreak leading to at least 50 infections. Columns headings 0%, 70%, 80%, and 90% refer to the percentage of 12-to-64-year-olds that are vaccinated in the community; all scenarios (except 0% coverage) assume 90% of over 65-year-olds are fully vaccinated. Results are from 100,000 independent simulations representing 100,000 infected travellers.

Post-arrival	Pre-depart	0%	70%	80%	90%
None	Symp check only	6	12	15	22
Regular symptom checks	No test	7	15	20	33
	PCR on day -3	7	15	20	32
	LFT on day -1	8	16	21	35
PCR on days 0 & 4	No test	8	21	30	52
	PCR on day -3	9	21	30	52
	LFT on day -1	9	22	31	56
Daily LFT for 5 days	No test	11	30	43	79
	PCR on day -3	12	30	44	82
	LFT on day -1	12	30	46	83
5 day isolation + PCR on days 0 & 4	No test	13	40	58	111
	PCR on day -3	14	39	61	109
	LFT on day -1	14	42	65	111
5 day isolation + daily LFT	No test	19	59	89	157
	PCR on day -3	19	58	90	154
	LFT on day -1	21	59	98	164
7 day MIQ + PCR on days 0 & 4	No test	649	>1000	>1000	>1000
	PCR on day -3	617	>1000	>1000	>1000
	LFT on day -1	641	>1000	>1000	>1000
14 day MIQ + PCR on days 3 & 12	No test	>1000	>1000	>1000	>1000
	PCR on day -3	>1000	>1000	>1000	>1000
	LFT on day -1	>1000	>1000	>1000	>1000

Table 8. Expected number of infected vaccinated travellers per large outbreak. Columns headings 0%, 70%, 80%, and 90% refer to the percentage of 12-to-64-year-olds that are vaccinated in the community; all scenarios (except 0% coverage) assume 90% of over 65-year-olds are fully vaccinated. Results are from 100,000 independent simulations representing 100,000 infected travellers. For scenarios in which less than 100 of the 100,000 simulations resulted in a large outbreak, the number of infected travellers per large outbreak is shown as >1000.

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Summary of vaccination, border testing and isolation modelling paper

From: COVID-19 Modelling Steering Group

Purpose

This note summarises the key results and limitations of the paper "Effect of vaccination, border testing, and quarantine requirements on the risk of COVID-19 in New Zealand: a modelling study".

Key points

Modelling has quantified the impact of testing and isolation requirements on the risk of onward transmission from an infected international arrival. This modelling suggests:

- rapid antigen pre-departure tests can reduce risk by as much or more than PCR pre-departure tests, as they can be performed closer to the time of departure.
- daily rapid antigen tests for recent arrivals can reduce risk as much or more than day-0 and day-4 PCR tests, by detecting infectious cases earlier.
- 7-day MIQ could allow for greater travel volumes with a relatively small increase in risk.
- 5-day self-isolation reduces but does not eliminate risk and could be used if combined with country-risk assessments and management of traveller volumes.
- higher domestic vaccination coverage reduces but does not eliminate the risk of large outbreaks.

This modelling has several limitations outlined further below. In particular, the risk experienced by New Zealand will also depend on the volume and COVID-19 prevalence of different traveller groups.

This modelling will inform further work including policy analysis of potential travel pathways, country risk assessments and travel volume modelling of different scenarios, and ongoing modelling of different strategies for managing COVID-19 with high vaccination coverage.

Background

As part of its Reconnecting New Zealanders plan, the Government has announced it will establish Low, Medium and High-Risk pathways for travel into the country, with the Medium-Risk pathway potentially including a combination of self-isolation and/or reduced MIQ[1].

To inform decisions on these risk pathways, the modelling paper quantifies the impact of testing and isolation requirements on the risk of onward transmission from an infected international arrival. The model also quantifies the probability of an infected traveller seeding a large outbreak with more than 50 infections at different rates of domestic vaccination coverage. The model considers options including pre-departure testing, testing once in New Zealand, self-isolation and 7-days in an MIQ facility.

[1] https://www.beehive.govt.nz/release/government-sets-out-plan-reconnect-new-zealanders-world

Results

Impact of testing

- Pre-departure testing results in a small relative reduction in risk of between 0-10% depending on the combination of other measures used.
- The modelling suggests that for pre-departure testing, rapid antigen tests may be more effective at reducing risk than PCR testing. Due to the lag between sample collection and returning results, PCR tests need to be performed a day or more prior to departure. Cases that have only recently been exposed may not be detected. Rapid antigen tests can be taken closer to the traveller's departure time, detecting cases that become infectious just prior to departure.
- The modelling suggests that for recent arrivals, daily rapid antigen testing for five days may be more effective at reducing risk than PCR tests on day 0 and day 4. While rapid antigen tests are less sensitive, repeated testing can increase the probability of detecting a case. In addition, the reduction in sensitivity for rapid antigen tests is smaller for cases that are in their peak infectious period. These cases contribute most to the risk of community transmission and outbreaks.
- These results suggest that rapid antigen tests can be used effectively to reduce risk, particularly when acceptability, timeliness and convenience are important.

Impact of self-isolation and 7-day MIQ

- Modelling suggests that a shorter period in MIQ could allow for greater travel volumes with relatively small increase in risk. Self-isolation reduces but does not eliminate risk. This suggests it can be used to manage risk, if combined with country risk assessments and management of traveller volumes.
- The table below presents results for four combinations of testing and isolation. Three measures of risk are shown: the probability of community transmission, the probability of a large outbreak, and the expected number of infected travellers that would result in one large outbreak. The table presents results assuming all travellers are vaccinated, undergo a PCR test three days pre-departure and that domestic vaccination coverage is 80% among over 15-year-olds. A wider set of scenarios are presented in the full paper.
- Five days in self-isolation reduces the probability of a large outbreak by two thirds compared with no testing and no isolation, and by half compared to testing alone. In comparison, seven days in MIQ reduces the probability of a large outbreak to close to zero.

	Probability of community transmission	**Probability of a large outbreak (50+ cases)**	**Expected number of infected travellers per large outbreak**
Infected vaccinated traveller	24%	4.9%	20
Infected vaccinated traveller + day-0 and day-4 PCR tests	23%	3.3%	30

	Probability of community transmission	Probability of a large outbreak (50+ cases)	Expected number of infected travellers per large outbreak
Infected vaccinated traveller + day-0 and day-4 PCR tests + 5-day self-isolation	17%	1.6%	61
Infected vaccinated traveller + day-0 and day-4 PCR tests + 7-day MIQ	0.6%	<0.1%	>1000

Impact of domestic vaccination

- The model shows that even with vaccination coverage of 90% of over 15-year-olds, borders cannot open without creating community outbreaks. This suggests managing border risk will continue to be important even after the vaccine rollout.
- Increases in vaccination coverage can materially reduce risk, even above already high levels. For example, increasing vaccination coverage from 0% to 80% of over 15-year-olds reduces the probability of a large outbreak by roughly 60%-80%. Increasing coverage from 0% to 90% reduces this probability by 70%-90%, a relative reduction of 30%-50% compared with 80% coverage.

Limitations

- The model quantifies risk for an infected traveller so does not consider the prevalence of COVID-19 or travel volumes. Changes in these factors can dominate the risk reduction from restrictions. For example, restrictions reducing risk by 10-fold combined with a 100-fold increase in infected travellers would result in a 10-fold total increase in risk. Given low current travel volumes and the wide variation of COVID-19 prevalence across countries, such large increases are plausible.
- The model does not fully capture the benefits of requiring travellers to be vaccinated. The model captures that vaccinated cases are roughly 50% less likely to transmit the virus. However, vaccinated individuals are also protected from infection, so will likely have lower prevalence of COVID-19.
- The model assumes self-isolation is 60% effective in reducing transmission for asymptomatic travellers and 80% effective for symptomatic travellers. These are rough assumptions given the limited data available on the effectiveness of self-isolation. Actual compliance could be significantly higher or lower depending on how self-isolation is implemented. Data from self-isolation pilots in New Zealand and overseas can be used to update these estimates.
- Modelling assumes no MIQ transmission to other arrivals, border workers or the community.
- The model uses international evidence on the sensitivity of rapid antigen tests. However, this evidence is evolving and may not reflect the tests and how they are used in New Zealand. This modelling can be updated as additional New Zealand and international data becomes available.

- Given the paper's focus on the border, the model includes simple assumptions about community settings such as community symptomatic testing and contact tracing, and does not model the use of higher Alert Levels. These factors will be considered in more depth in ongoing modelling of different strategies for managing COVID-19 with high vaccination coverage.
- The model is based on the characteristics of the Delta variant and current estimates of the effectiveness of the Pfizer vaccine. Travellers vaccinated with other vaccines, waning of immunity and future variants may significantly impact these results.
- The model considers vaccination coverage of over 15-year-olds, based on the previous eligible population. These results can be updated for coverage of over 12-year-olds and over 5-year-olds. Modelling of different COVID-19 strategies will focus on these age groups.

Next steps

- Together with other evidence and policy analysis, this modelling will inform the tools that could be used in different travel pathways and the thresholds and requirements for entering these pathways.
- This modelling can be combined with country risk assessment modelling and different travel volume scenarios to give a more complete picture of how different policy options affect the risk of community outbreaks. This will also inform ongoing modelling over the next month of different strategies for managing COVID-19 with high vaccination coverage.

From:	Christopher Nees [TSY]
To:	Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; xxxxx.xxxxxx@xxxxx.xxxx.xx; Ian Town; pmcsa; ^EXT: Talosaga Talosaga; x.xxxxxxx@xxxxxxx.xx.xx
Cc:	George Whitworth [DPMC]; xxxxxxxx.xxxxxxxx@xxx.xxxx.xx ; Gill Hall; xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx ; Patricia Priest; xx@xxxxx.xx.xx ; Caleb Morrall [TSY]; Harry Nicholls [TSY]
Subject:	Agenda and papers for Friday"s Covid-19 Modelling Governance Group
Date:	Wednesday, 1 September 2021 11:21:00 AM
Attachments:	4511535_4482665_Agenda - COVID Modelling Governance Group meeting 3 September.DOCX image001.png 4501433_Interpreting the border testing and quarantine paper.PDF v0.7 Vaccination and Border Testing.docx v0.7 Additional Outbreak Results.docx 4499477_Modelling approaches to managing COVID (DRAFT).DOCX image002.png

Kia ora koutou
Please find attached an agenda and papers for Friday.

Ngā mihi

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I do not work on Thursdays.

From: Christopher Nees [TSY]
Sent: Tuesday, 31 August 2021 2:01 PM
To: Bryan Chapple [TSY] <x@xxx; ^MBIE: Paul Stocks <x@xxx; ^MSD: Nic Blakeley <x@xxnz>; Cheryl Barnes [DPMC] <x@xxx; x@xxIan Town <x@xxx; pmcsa <x@xxx; ^EXT: Talosaga Talosaga <x@xxx; x@xxx
Cc: George Whitworth [DPMC] <x@xxx; x@xxGill Hall <x@xxx; x@xxPatricia Priest <Patricia.Priest@health.govt.nz>; x@xxCaleb Morrall [TSY] <x@xxx; Harry Nicholls [TSY] <x@xxx
Subject: RE: Covid-19 Modelling Governance Group

Kia ora koutou

Our proposed agenda for this Friday is:

1. An overview of the modelling on the current resurgence. This is to give you a picture of the latest work and understand our modelling cycle with TPM.
2. Latest draft results on the 'border reopening scenarios' paper. We introduced this work at the last meeting and have an updated but not final draft from TPM
3. Proposed modelling work on options for managing COVID-19 as vaccination rates increase. This work is similar to what has been recently undertaken in Australia and aims to look at what bundles of public health restrictions are sufficient to control resurgences when vaccination rates are high, how long they are needed for, and their economic impacts.

Please let me know if you have further items you'd like to cover.

Ngā mihi

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-
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-

-----Original Appointment-----
From: Steph Tims [TSY] <x@xx> **On Behalf Of** Bryan Chapple [TSY]
Sent: Wednesday, 18 August 2021 5:05 PM
To: Bryan Chapple [TSY]; Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; x@xx; Ian Town; pmcsa; ^EXT: Talosaga Talosaga; x@xx; Christopher Nees [TSY]; Harry Nicholls [TSY]; Caleb Morrall [TSY]
Cc: George Whitworth [DPMC]; x@xx; Gill Hall; x@xx; Patricia Priest; @xx
Subject: Covid-19 Modelling Governance Group
When: Friday, 3 September 2021 12:45 PM-1:30 PM (UTC+12:00) Auckland, Wellington.
Where: (MS Teams); +TSY 3.30 Purapura -46 -MS Teams (EXT)

Hi all –
Rescheduling this from 20/8 to 3/9 – apologies for hijacking the lunch break!
Agenda and papers will be circulated in advance.

Cheers. Steph

Steph Tims (she/her) | **Te Tai Ôhanga – The Treasury**
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Agenda: COVID-19 Modelling Governance Group 3 September 2021

Chair: Bryan Chapple, Deputy Secretary, Macroeconomics and Growth, **The Treasury**

Members: **DPMC**: Cheryl Barnes, **MOH**: Ian Town, Talo Talosaga **MBIE:** Paul Stocks, **StatsNZ:** Vince Galvin **MSD:** Nic Blakeley, **PMCSA**: Juliet Gerrard.

1. **Welcome and apologies** (apologies from Nic)

2. **General updates/context (all)**

   Purpose: To share information on recent developments. Possible items include:

   - Recent discussion with Sir David Skegg on modelling work (George)

3. **An overview of the modelling on the current resurgence (George)**

   Purpose: To give you a picture of the latest modelling of the current resurgence and understand our modelling cycle with TPM.

4. **Update and summary of TPM's border testing and quarantine paper (Chris)**

   Purpose: to discuss the key results of TPM's modelling work on border reopening.

   Papers: Interpreting the border testing and quarantine paper (summary from Officials), Vaccination and Border Testing (paper from TPM), Additional Outbreak Results (paper from TPM)

   Context: Since your last meeting TPM has progressed this paper that looks at the risks from different forms of border reopening. The paper is undergoing technical and public health review before briefing Ministers and publication (timing TBC).

5. **Modelling to support management of COVID-19 at high levels of vaccination (Chris)**

   Purpose: To share and seek feedback on proposed modelling to understand what degree of public health restrictions would manage COVID when community vaccination is high

   Papers: Modelling approaches to managing COVID-19

   Context: We are commissioning modelling from TPM to help understand what 'bundles' of public health restrictions would be sufficient to manage COVID outbreaks once community vaccination is at high levels. This is similar to recent work in Australia that found permanent 'baseline' restrictions (limiting venue capacity, square metre rules) were the most effective way to manage COVID so as to not exceed the limits of the contact tracing system.

   Importantly such modelling needs to be informed by assessments of 'real world' re-openings, for example in Singapore. This work is also being progressed by DPMC.

6. **Any other business (Bryan)**

   Purpose: To discuss any outstanding matters.

Interpreting the Vaccination and Border Testing paper

For: Modelling Governance Group, 3 September

From: Modelling Steering Group

Why was this modelling commissioned?

- The purpose of this modelling is to quantify the relative risk of community outbreaks using different bundles of mitigation measure for international travellers arriving into New Zealand
- The model assesses the "transmission potential" of a traveller with different border/arrival interventions, the risk of onward transmission into the community from a traveller, and the probability of an infected traveller starting a large outbreak.
- The model is therefore useful to inform policy decisions about options for how the border could be opened in different ways, as the vaccine rollout continues.

What are the key results?

The paper sets out the impact of using many different combinations of pre-departure and arrival measures to manage risk. For simplicity the table below focusses on results that relate to:

- reopening only to vaccinated travellers
- reopening only where community vaccination reaches 80%
- reopening scenarios using three 'bundles of interventions': daily testing, 5 day self-isolation, and 7 day MIQ

The results are best interpreted as providing a sense of the relative risk of different options, rather than precise estimates that predict outcomes.

	Reduction in transmission potential (relative to non-vaccinated traveller with no pre-departure testing)	Probability of onward transmission from an infected traveller with 80% community vaccine coverage	Probability of a large outbreak from an infected traveller with 80% vaccine coverage	Number of travellers per large* outbreak with 80% vaccine coverage
Vaccinated traveller	50%	15%	8%	13
Daily LFT tests for 5 days	77%	8%	4%	25
5 day self isolation with daily rapid tests	90%	5%	2%	50-54
7 day MIQ with PCR testing	99.8%	0.1%	0.1%	1000+

What are the notable results?

- The model shows there is no point at which vaccination rates mean that borders can open without creating community outbreaks (noting that the maximum modelled vaccination coverage is 90% of 16+ year olds).

- High levels of community vaccination make a material reduction to the risks from international arrivals. For example, with 60% vaccination rates, the risk of a large outbreak is 40-50% higher than if community vaccine coverage is 80%.
- Vaccination status has the largest single effect in reducing transmission potential of a traveller, followed by the use of post-arrival restrictions. Pre-departure tests have a small effect.
- Rapid antigen tests look like a particularly useful intervention to use to test frequently and quickly, supplemented with some PCR testing. (noting there is large variability around the type and effectiveness of these tests).
- While the model assumes vaccinated infected travellers are 50% as "risky" as non-vaccinated travellers, they are also less likely to be infected in the first place. This means they are even less "risky" than this analysis would otherwise suggest.

What are some of the limitations/key points of interpretation?

- The model is not set up to consider differences in traveller risk which we know will vary according to where they have spent the previous 14 days before arriving in NZ. This suggests the results may be pessimistic if considering arrivals from low-risk countries, but optimistic if the arrivals are from high-risk countries. More permissive entry requirements may be appropriate for the former, but the more restrictive measures would be necessary for the latter.

- Travel volumes also matter. If restrictions are implemented that reduce the risk 10 fold, but there is a 100 fold increase in travellers (or increase in travellers from high risk countries such that the number of infected travellers increases 100 fold), then there will be a 10 fold increase in risk.

- The model assumes self-isolation is 60% effective in reducing transmission for asymptomatic travellers and80% effective for symptomatic travellers. The actual rate would reduce if there is poor compliance but improve if there were policies such as requiring household contacts to be vaccinated or with mechanisms to 'enforce' self isolation.

- The model assumes contact tracing is the only intervention used to manage instances of community transmission and that there are no 'baseline' public health measures in place (e.g. mandated mask wearing, permanent limits on venue capacity etc). This may mean that the risks of community outbreaks are overstated because public health restrictions are likely to be used in response to case identification.

- The model also assumes a relatively low rate of community testing (12% of symptomatic individuals), reflecting experience, but interventions to increase this rate would mean cases are detected more quickly and potentially avoid large outbreaks.

- The model does not show the health impacts of these outbreaks, which will become smaller (but never zero) with higher levels of vaccination. In other words, understanding health outcomes rather than case numbers will become more important when vaccination levels are high.

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Effect of vaccination and border testing and quarantine requirements on the risk of COVID-19 in New Zealand: a modelling study

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Abstract

We couple a simple model of quarantine and testing strategies for international travellers with a model for transmission of SARS-CoV-2 in a partly vaccinated population. This is used to consider the risk reduction achieved from implementing various non-pharmaceutical interventions at the border as well as the implications for onward spread in the community. Key outputs include the reduction in transmission potential from various strategies, the probability that an arrival triggers a “serious” outbreak, and the expected frequency of such outbreaks. Various definitions of “serious” are considered.

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Introduction

Since April 2020, New Zealand has pursued a COVID-19 elimination strategy and, through a combination of strict border controls and snap lockdowns when needed, has seen very limited community transmission since the last significant outbreak in August 2020 (REF Baker et al). As a result New Zealand has negligible infection-acquired immunity to COVID-19 (REF antibody study). New Zealand's national vaccination programme began in February 2021 and is using the Pfizer/BioNTech mRNA vaccine. As of mid-August 2021, around 16% of the population are fully vaccinated and an additional 10% have received their first dose [1]. The government aims to offer the vaccine to everyone who is eligible by the end of 2021

During 2021, the Delta variant of SARS-CoV-2 has displaced other variants and become dominant in many countries, including India, the UK and USA – countries with which New Zealand has close travel links. Because of the increased transmissibility of the Delta variant, it is unlikely that countries will be able to reach complete population immunity (i.e. a reproduction number that less than 1 in the absence of any other interventions) via vaccination alone [2]. Other public health measures will be needed to control the virus, although reliance on these will reduce as vaccine coverage increases. These measures may consist of a mixture of border controls designed to reduce the risk of cases being seeded into the population, and community measures designed to enhance surveillance and reduce the potential for transmission.

With current levels of vaccine coverage and given the increased transmissibility of the Delta variant, New Zealand's current requirement of 14 days in government-managed isolation for international arrivals is still needed to prevent the virus entering the community. At present, any border-related cases would have the potential to cause rapidly growing community outbreaks that would be impossible to control without lockdown measures [2]. However, once vaccination coverage is sufficiently high, it will be possible to gradually relax border controls in conjunction with ongoing community public health measures. To do this safely, it will be important to quantify the relative risk of community outbreaks under different sets of mitigation measures for international travellers arriving to New Zealand. These may include

different combinations of government-managed isolation and quarantine (MIQ), self-isolation at home, and pre-departure and post-arrival testing requirements. Different sets of requirements could be applied to travellers depending on their risk profile, for example more stringent restrictions for people travelling from countries with high infection rates.

New Zealand has primarily used RT-PCR tests for SARS-CoV-2 testing throughout the pandemic, sometimes known as the gold standard test because of its high sensitivity. Around the world, countries are increasingly complementing PCR testing with rapid antigen tests, also known as lateral flow tests. These have lower sensitivity that PCR tests, particularly in the early and late stages of the infectious period [3]. However, they have the advantage that they return results very quickly (typically within 30 minutes), they are cheap, and they do not require lab processing. This means they can be used to test large numbers of people at high frequency (e.g. daily) without stretching lab capacity and with fast turnaround of results.

Travel volume is a key determinant of the risk posed by international travel. As a consequence of limited MIQ capacity and citizenship or residence requirements for entry, the volume of international arrivals to New Zealand has been approximately 2% of pre-pandemic levels (with the exception of arrivals from Australia during limited periods of quarantine-free travel). It is important to factor this into risk evaluations because if, for example, a given mitigation provides a 10-fold reduction in the risk per arrival, this will be offset if there is a simultaneous 10-fold increase in travel volume.

In this paper, we use a stochastic model of SARS-CoV-2 transmission and testing to compare the relative reduction in transmission potential from infected travellers under various mitigations and at different levels of vaccine coverage in the resident population. This paper is a policy-oriented application of the model developed by [2] to investigate the potential impact of COVID-19 at different stages in New Zealand's vaccination programme.

The model allows for different effectiveness of isolation under different circumstances, for example MIQ versus self-isolation at home during asymptomatic, pre-symptomatic, symptomatic or confirmed stage of infection. We compare different testing requirements, such as daily LFTs or less frequent PCR tests, allowing for the different sensitivity of these

tests. The model also includes individual heterogeneity in transmission rates and the probability of returning a positive result if tested.

We use the model to simulate community outbreaks seeded by international arrivals and calculate the probability that such an outbreak meets various pre-defined criteria. The aim is not to identify vaccination targets at which borders can be completely reopened, but rather to support strategies for safe relaxation of travel restrictions by comparing the risk reduction from various policy options.

The modelling approach is similar to that of Quilty et al, who estimated the reduction in transmission potential from a range of traveller interventions. The model of Quilty et al modelled individual heterogeneity in viral load trajectories and effectively assumed a one-to-one mapping between viral load, transmission rate and probability of testing positive. We found it difficult to reconcile this with the fact that there is significant pre-symptomatic transmission of SARS-CoV-2 and that the likelihood of individuals testing positive in the pre-symptomatic stage appears to be significantly lower than after symptom onset. We therefore take a simpler approach based on an empirically estimated generation time interval and test positivity curve and we investigate the qualitative effects of different forms of heterogeneity in these.

Methods

Age-structured transmission model

We model transmission of SARS-CoV-2 using the stochastic age-structured branching process model described in [2]. This subsection gives a brief summary of the main model assumptions – for technical details see [2].

We use the same vaccine effectiveness and vaccine sequencing assumptions as [2]. This means that vaccine allocation is assumed to be static (we do not consider simultaneous

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dynamics of community transmission and an ongoing vaccination programme) and we consider different levels of vaccine coverage. For a given level of vaccine coverage, we assume that vaccines are prioritised to the over-65-year-old age group, up to a maximum coverage of 90%; remaining vaccines are allocated uniformly to the 15-65-year-old group. For simplicity, we assume all individuals are either fully vaccinated or non-vaccinated (i.e. we do not consider the effect of people who have had a single dose). We assume the vaccine prevents infection in $e_I = 70\%$ of people, and reduced transmission by $e_T = 50\%$ in breakthrough infections. This provides an overall reduction in transmission of 85% (REF SPI-M paper). We assume that the vaccine effectiveness against symptomatic disease is the same as the vaccine effectiveness against infection e_I (this assumption will be tested in future sensitivity analysis). This does not preclude higher vaccine effectiveness against severe illness or death, although we do not investigate these outcomes in this study.

Transmission between age groups is described by a next generation matrix, whose (i, j) entry is defined to be the expected number of secondary infections in age group i due to an infectious person in age group j in the absence of interventions and given a fully susceptible population:

$$NGM_{i,j} = Uu_i t_I C_{j,i}$$

where u_i is the relative susceptibility to infection of age group i, C is a contact matrix describing mixing rates between and within age groups [4], t_I is the average infectious period and U is a constant representing the intrinsic transmissibility of the virus.

Infected individuals are categorised as either clinical or subclinical, with the clinical fraction increasing with age (see Table 1b). Clinical individuals are assigned a symptom onset time which is Gamma distributed from exposure time with mean 5.5 days and s.d. 3.3 days [5]. In the absence of interventions, we assume generation time are drawn from a Weibull distribution with mean 5.0 days and s.d. 1.9 days [6]. Subclinical individuals are assumed to be $\tau = 50\%$ as infectious as clinical individuals.

All individuals are assigned a gamma distributed random variable Y_l with mean 1 and variance $1/k$, such that the expected number of secondary cases infected by individual l given a fully

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susceptible population in the absence of interventions (the individual reproduction number) is

$$R_l = (1 - V_l e_T) Y_l \sum_{j=1}^{M} NGM_{j,a_l}$$

where $V_l = 1$ if individual l is vaccinated and zero otherwise, and e_T is the vaccine effectiveness against transmission conditional on infection. The expression above is multiplied by τ if individual l is subclinical. This allows for individual heterogeneity in transmission.

Testing

Travellers are assigned curves representing the probability of testing positive as a function of time since exposure. For RT-PCR tests we use data from [4], with a peak probability of testing positive of 81% eight days after infection, and for LFT tests we use data from [7], scaled so they have a peak probability of 73% (90% of the PCR peak) and shifted so this peak occurs at the same time as the PCR curve (see Figure 1).

In addition, we assume that it is not possible to test negative by PCR and positive by LFT on the same day. To generate an LFT result, we therefore simulate the result of a putative PCR test where probability of a positive result is as shown by the blue curve in Fig. 1. If the putative PCR result is negative, we assume the LFT result is also negative. If the putative PCR result is positive, we assume the LFT result is positive with probability $P(LFT^+|PCR^+) = P^+_{LFT}(t)/P^+_{PCR}(t)$, which is the ratio of the blue curve to the red curve in Fig. 1.

The overall shape of these curves implies a protocol sensitivity of 77% (PCR) and 60% (LFT) for a test taken randomly within one week from symptom onset, and 66% (PCR) and 33% (LFT) for a test taken randomly within two weeks from symptom onset.

For the base model, we ignore individual heterogeneity in probability of testing positive at a given time after infection but test sensitivity to this assumption (see Individual Heterogeneity subsection below). We also assume that the results of multiple tests on the same individual on different days are independent. The probability of testing positive is assumed to be the same for subclinical and clinical individuals. Conditional on getting infected, the probability of testing positive is assumed to be the same for vaccinated as for non-vaccinated individuals. is assumed to be the same for vaccinated as for non-vaccinated individuals.

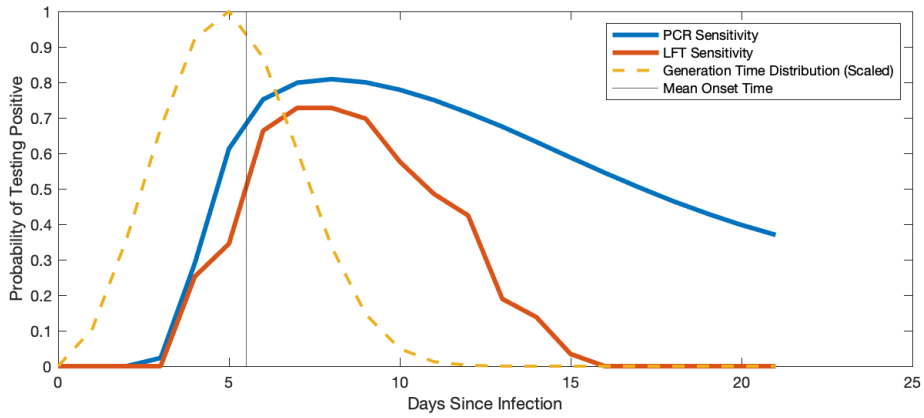

Figure 1. Assumed probability of testing positive as a function of time since infection for PCR (blue) and LFT (red). Dashed curve shows the scaled generation time distribution, showing that a large amount of transmission occurs prior to test positivity.

It is clear from Figure 1 that, under these assumptions, a significant amount of transmission occurs before the infected person has a reasonably high probability of testing positive. This may seem pessimistic but it is consistent with the fact that pre-symptomatic transmission of SARS-CoV-2 is known to be common and with empirical data showing that the probability of testing positive prior to symptom onset is smaller than after symptom onset [4].

Border interventions

We test the effects of a set of interventions depending on policy scenarios (see below) on the expected transmission from an infected traveller. We use $F_l^c(t)$ to denote the transmission rate of individual l at time t under a given intervention c, relative to their unmitigated transmission rate at time t. When $F_l^c(t) = 1$, this means individual l is not quarantined or isolated at time t; when $F_l^c(t) = 0$, this means individual l is fully isolated at time t and

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cannot transmit the virus. Note that $F_l^c(t)$ is also defined to be zero if individual l has not yet arrived at their destination, or has been prevented from travelling from pre-departure symptom checks or testing. The expected number of secondary cases caused by individual l under interventions c relative to no interventions is given by:

$$\frac{R_l^c}{R_l} = \int_0^\infty F_l^c(t)\omega(t)\,dt$$

where $\omega(t)$ is the probability density function for the generation time distribution.

Interventions can be split into three categories: vaccination status, pre-departure tests, post-arrival restrictions. We consider a few key policies for each category in Table 1. All scenarios assume a baseline level of screening passengers so that 80% of travellers who develop symptoms prior to departure are prevented from travelling, independent of any tesing requirements.

Vaccination	Pre-Departure	Post-Arrival
Fully vaccinated	No test	No requirements
Not vaccinated	PCR on day -3	PCR on days 0 & 4
	LFT on day -1	Daily LFT for 5 days
		5 day self-isolation with PCR on days 0 & 4
		5 day self-isolation with Daily LFT for 5 days
		7 days MIQ + day 5 PCR
		Full 14 day MIQ + 2 tests

Table 1. Overview of key policies considered for international travellers.

[FLOWCHART DIAGRAM TO GO HERE]

Self-isolation after arrival can occur for any one of four reasons:

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- Due to a requirement to self-isolate while asymptomatic, assumed to reduce transmission by 60% ($F_l^c(t) = c_{asymp} = 0.4$).
- Due to onset of symptoms, assumed to reduce transmission by 80% ($F_l^c(t) = c_{symp} = 0.2$), regardless of the isolation policy. Isolation is assumed to begin on the day following symptom onset. This might represent a situation where recent arrivals are contacted by public health teams to encourage monitoring of symptoms.
- Due to return of a positive test, assumed to reduce transmission by 100% ($F_l^c(t) = c_{conf} = 0$), regardless of the isolation policy. Isolation is assumed to begin on the day following the return of a positive result.
- Due to a requirement to enter MIQ, assumed to reduce transmission by 100% ($F_l^c(t) = c_{MIQ} = 0$).

Individuals isolate with the effectiveness of the strongest measure that applies at time t. This formulation assumes that all isolated individuals transmit at a reduced rate c. However, we expect average model outputs to be very similar if we instead assumed that a fraction c of isolated individuals do not transmit at all, and a fraction $1 - c$ transmit at the same rate as a non-isolated individual.

Individuals that develop symptoms after arrival seek a test with probability 80%. This test is assumed to be a PCR test taken with an exponentially distributed delay with mean 2 days after symptom onset and the result is returned the following day. If the individual is scheduled for any kind of test on the same day, they do not take the additional test.

Branching process model for community outbreaks

At each timestep of size Δt, infected individuals generate a Poisson distributed number of secondary cases with mean:

$$\lambda(t) = R_l \int_t^{t+\Delta t} F_l^c(x)\omega(x)\, dx$$

where $F_l^c(x)$ describes the reduction in transmission due to isolation or prevention of travel (see above) and $\omega(x)$ is the probability density function for the generation time distribution.

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Each secondary case is assigned an age-group i with probabilities proportional to the $a_l{}^{\text{th}}$ column of the next-generation matrix (corresponding to the index cases' age-group). These cases are assigned to the vaccinated class with probability v_i. The would-be secondary cases that are vaccinated are then thinned with probability e_I, the assumed vaccine effectiveness against infection. Population immunity due to prior infection is ignored in the model. This is reasonable because we only consider small community outbreaks and pre-existing immunity due to infection is negligible in New Zealand.

By default we assume $R_0 = 6.0$ for all simulations, approximately representing the Delta variant of SARS-CoV-2 (REF, e.g. one of the SPI-M papers) and that arriving travellers have the same age distribution and contact matrix as the New Zealand population.

We use a simplified model for case-targeted controls in the community. We assume there are initially no controls in place in the period of time before the outbreak is detected (i.e. before the first positive test result is returned). Outbreaks can be detected either via a positive test result in the infected traveller or by community testing. During the period before the outbreak is detected, we assume that symptomatic individuals in the community are tested with probability $p_{test,pre}$ 0.12. Once an outbreak has been detected, all existing and subsequent cases in the outbreak are detected with probability $p_{test,outbreak}$ 0.4 and isolated with a mean delay of 2 days after symptom onset. To model the effect of contact tracing, we also assume that cases are traced with probability p_{trace} 0.7 and isolated with a mean delay of 6 days after infection (see Table 1b).

Individual heterogeneity in probability of testing positive

In the base model, we ignore heterogeneity between individuals in the probability of testing positive at a given time. In reality, there may be variability in the timing, magnitude and duration of the probability of testing positive, and these may be correlated with individual infectiousness. This could affect the performance of different risk mitigation strategies. However, explicitly modelling these heterogeneities and correlation would require data on the probability of testing positive and infectiousness, stratified by individual and time. In the absence of detailed data on this, we consider a simplified model for individual heterogeneity.

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The base model described above includes heterogeneity in transmission, via the individual parameter Y with mean 1 and variance $1/k$. To introduce heterogeneity in probability of testing positive, we let $Y = Y_1 Y_2$ where Y_1 and Y_2 are independent random variables. This characterisation decomposes individual heterogeneity in transmission into a contribution Y_1 that is independent of the probability of testing positive and a contribution Y_2 that is related to the probability of testing positive. Conceptually, Y_1 quantifies behavioural factors that drive transmission (i.e. contact rates during the infectious period), whereas Y_2 is related to biological characteristics of the viral infection (e.g. viral load) in a particular individual. By adjusting the variance of Y_1 while holding the variance of Y fixed, we can vary the extent to which individual transmission is correlated with probability of testing positive. In the base model, $Var(Y_2) = 0$ meaning there is no heterogeneity in probability of testing positive and so heterogeneity in transmission rates are entirely due to individual differences in contact rates.

To realise this model we assume Y_1 is gamma distributed with mean 1 and variance $1/k^*$ and Y_2 is normally distributed with mean 1 and varaicne σ^2, truncated to non-negative values. If we set $k^* = k(1+\sigma^2)/(1-k\sigma^2)$, then provided σ^2 is sufficiently small, Y is approximately gamma distributed with mean 1 and variance $1/k$, as for the base model. A test result for individual l at time t is then generated as an independent Bernoulli random variable with mean $\frac{y_{2,l}P^+(t)}{1-(1-y_{2,l})P^+(t)}$, where $y_{2,l}$ is the value of the random variable Y_2 for individual l and $P^+(t)$ is the relevant test positivity curve for either PCR or LFT shown in Figure 1.

Model Outputs

For each set of interventions c, we run $N = 10{,}000$ simulations, each initialised with one infected traveller. The traveller is assigned an age-group with a frequency proportional to the New Zealand age-structure, an infection time uniformly randomly distributed in the 14 days prior to arrival, and a clinical status that depends on age. The simulation returns the

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transmission potential of the infected traveller (R_I^c) and a list of any infections in the community. From these simulations, we report three model outputs defined as follows.

Output (1) is the transmission potential of infected arrivals under interventions c relative to the transmission potential in the absence of interventions. This is defined as $\overline{R_I^c}/\overline{R_I^0}$ where the bar denotes the mean of N simulations.

Output (2) is the proportion of simulations meeting each of the following four criteria: (i) the infected traveller causes any onward transmission in the community; (ii) the infected traveller causes onward transmission in the community and is never detected; (iii) the infected traveller leads to an outbreak that reaches 5 infections; (iv) the infected traveller leads to a large outbreak that reaches 50 infections. Note that because the reproduction number is significantly greater than 1, even at the highest vaccine coverage level considered (90% of over-15s), outbreaks that reach 50 infections are almost certain to continue to grow indefinitely until control measures are introduced (or there is a build-up of population immunity). The criteria of 50 infections is arbitrary, but is a convenient point at which to terminate simulations and indicates that community transmission has become established. For context, this threshold is approximately the number of people who were already infected at the time the Auckland outbreak in August 2020 was detected.

Finally, output (3) is the number of infected travellers who would be expected to result in one large outbreak (that reaches 50 cases from one traveller). If, for example, an average of one outbreak *per month* is tolerable, then this is the number of infected travellers who would be tolerated per month. This is equal to the reciprocal of the probability that an infected arrival starts a large outbreak.

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Parameter	Value
Basic reproduction number in the absence of control	$R_0 = 6$
Relative transmission rate for isolated individuals:	
- asymptomatic / pre-symptomatic	$c_{asym} = 0.4$
- symptomatic	$c_{symp} = 0.2$
- confirmed cases	$c_{conf} = 0$
- in MIQ	$c_{MIQ} = 0$
Incubation period	Mean 5.5 days, s.d. 3.3 days
Generation interval	Mean 5.0 days, s.d. 1.9 days
Relative infectiousness of subclinical individuals	$\tau = 0.5$
Heterogeneity in individual reproduction number	$k = 0.5$
Vaccine effectiveness:	
- against infection	$e_I = 0.7$
- against transmission in breakthrough infection	$e_T = 0.5$
Probability of a clinical community case being tested:	
- before an outbreak is first detected	$p_{test,pre} = 0.12$
- after an outbreak is detected	$p_{test,outbreak} = 0.4$
Mean time from symptom onset to test result:	
- before an outbreak is first detected	~~2~~ 4 days
- after an outbreak is detected	~~2~~ 4 days
Probability of a community case being detected via contact tracing	$p_{trace} = 0.7$
Mean time from infection to quarantine for traced contacts	6 days
Probability of testing positive by PCR on days $[1, \dots, 21]$ after infection	[0, 0.01, 0.04, 0.33, 0.62, 0.75, 0.79, 0.80, 0.79, 0.77, 0.73, 0.70, 0.66, 0.62, 0.57, 0.52, 0.48, 0.44, 0.40, 0.37, 0.34]
Probability of testing positive by LFT on being PCR positive on days $[4, \dots, 15]$ after infection	[0.25, 0.35, 0.66, 0.73, 0.73, 0.70, 0.58, 0.49, 0.42, 0.19, 0.14, 0.03]

Age-specific parameters																
Age (yrs)	0-4	5-9	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75+
% of popn	5.98	6.39	6.56	6.17	6.59	7.40	7.44	6.62	6.08	6.41	6.43	6.38	5.77	4.90	4.24	6.64
Pr(clinical) (%)	54.4	55.5	57.7	59.9	62.0	64.0	65.9	67.7	69.5	71.2	72.7	74.2	75.5	76.8	78.0	80.1
Susceptibility*	0.46	0.46	0.45	0.56	0.80	0.93	0.97	0.98	0.94	0.93	0.94	0.97	1.00	0.98	0.90	0.86

Table 1b. Parameter values used in the model. *Susceptibility for age group i is stated relative to susceptibility for age 60-64 years.

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Results

Relative Transmission Potential

The relative transmission potential measures the reduction in the expected number of secondary cases per infected traveller as a result of a given border intervention c. By construction, the relative transmission potential measures of the effectiveness of a given border intervention in reducing risk, independent of the assumed value of R_0 and of the level of vaccine coverage in the domestic population. For example, a set of interventions for which the relative transmission potential is 0.6 means that an individual infected traveller under this intervention is on average 60% as risky as they would be with no interventions.

Table 2 gives the relative transmission potential of an average infected traveller under a given border policy. All results are relative to the same baseline, representing the transmission potential of a non-vaccinated traveller that faces no interventions other than a pre-departure symptom check. Conditional on being infected, a vaccinated individual is assumed to be approximately 50% as infectious as a non-vaccinated individual (Table 1b). However, it is important to note that these individuals, depending on the vaccination rates and prevalence of infection in country of origin, are less likely to be infected than a non-vaccinated person in the first place.

The introduction of regular symptom checks post-arrival and isolation (assumed to be 80% effective from the day following symptom onset) for symptomatic arrivals reduces the transmission potential to 77% of the baseline (unmitigated) transmission potential for non-vaccinated travellers and 39% for vaccinated travellers.

The addition of a pre-departure testing requirement provides a relatively small reduction in transmission potential (for vaccinated travellers from 39% with no pre-departure testing to 38% for PCR on day -3 or 36% for LFT on day -1). Although pre-departure testing and symptom checks screens out a significant number (approximately 34% for symptom-checks only, 54% with the addition of either test) of travellers, many of these travellers would have been

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towards the end of their infectious period by the time they arrived at their destination. This is why the reduction in transmission potential is relatively small. The small difference between the effect of a PCR tests on day -3 and a LFT test on day -1 suggests the reduced sensitivity of the LFT is roughly offset by the fact it can be done closer to the time of departure.

Of the post-arrival testing strategies, a daily LFT for 5 days is more effective (reducing transmission potential from 39% to 23% for vaccinated arrivals) than PCR tests on day 0 and day 4 (39% to 33%). This shows that, under the assumed test characteristics, the lower sensitivity of LFT tests is outweighed by the increased frequency of testing and faster return of results.

Adding a requirement for five days self-isolation after arrival further reduces transmission potential (from 33% to 15% with the PCR testing strategy and from 23% to 10% with the LFT strategy, for vaccinated arrivals). Finally, a seven day stay in MIQ with two PCR tests reduces transmission potential to approximately 0.2% for vaccinated travellers, and a fourteen day stay in MIQ with two PCR tests reduces risk to near zero.

Risk of Onward Transmission

Table 3 gives the probability that an infected traveller leads to any onward transmission in the community and Table 4 gives the probability that an infected traveller leads to any onward transmission and is not detected by testing. Table 5 gives the probability that an infected traveller starts an outbreak that reaches at least 5 cases, and Table 6 gives the probability that an infected traveller starts an outbreak that reaches at least 50 cases. These risks all decrease as the vaccine coverage in the resident population increases. The latter two tables assume a moderately effective contact tracing process begins once an infection has been detected (either via a positive test result in the traveller who triggered the outbreak or a detection via community testing). The results are presented for both vaccinated and non-vaccinated travellers in the tables, although we focus on vaccinated travellers in the results discussed below.

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When only pre-departure symptom checks are included, there is a 26% chance that an infected traveller leads to onward transmission (both all & undetected) for a fully susceptible population (i.e. no vaccine coverage). This decreases to 19% when 90% of the domestic population aged 15-years or over are vaccinated. Note that population vaccine coverage only reduces the risk of onward transmission due to the infection blocking aspect of the vaccine, which is assumed to have an effectiveness of $e_I = 70\%$. The risk of an outbreak to a certain size (see Tables 5 and 6 described below) is further reduced by the transmission reducing aspect of the vaccine

The addition of post-arrival symptom checks results in a modest reduction in the probability of onward transmission (23% without domestic vaccination, decreasing to 17% at 90% coverage of over-15s). This decreases to 22%/17% with the addition of a pre-departure PCR test, or to 21%/15% with the addition of a pre-departure LFT test.

Consistent with the results in Table 2, daily LFTs for 5 days after arrival makes the risk of onward transmission smaller (16% with no vaccine coverage, dropping to 11% at 90% coverage of over-15s) than PCR tests on day 0 and day 4 (21% with no vaccine coverage dropping to 15% at 90% coverage of over-15s). The daily LFT strategy also performs better at preventing onward transmission where the infection in the traveller is not detected (2.4% for LFT compared to 3.2% for PCR with no domestic vaccination), although see below for effects of individual heterogeneity.

When five days of self-isolation are required we again find that daily LFT tests perform better at preventing any onward transmission (7.6% for LFT compared to 11% for PCR with no domestic vaccination), and better at preventing onward undetected transmission (2.0% for LFT compared to 2.8% for PCR).

Comparing Tables 5 and 6 suggests that, in a non-vaccinated population, most outbreaks that reach five cases also go on to reach fifty cases, as the respective probabilities are very similar. These scenarios assume effective contact tracing is implemented once an outbreak is detected, so while vaccination levels are low, additional controls would almost always be necessary to control an outbreak.

High levels of community vaccine coverage decreases the risk that a vaccinated traveller with only pre-departure symptom checking starts a large outbreak from 17% with no vaccination, to 5.5% with 90% of 15+ year-olds vaccinated. Introducing a pre-departure LFT and domestic symptom checks decreases this to 3.8%. Further introducing a daily LFT for 5 days post arrival takes this to 2.5%, or a PCR test on day 0 and 4 takes this to 3.5%. Including 5 days of self-isolation reduces the risk with LFT tests to 1.4% and the risk with PCR tests to 1.9%. These results can also be interpreted in terms of the number of infected travellers that are expected to lead to one large outbreak (Table 7).

Aside from those involving MIQ, the only scenario that consistently tolerates more than 50 infected travellers per large outbreak is 5 day self-isolation with daily LFTs and 80%+ domestic vaccine coverage, or 5 day self-isolation with two PCR tests and 90% vaccine coverage. There is no scenario where domestic vaccine coverage is below 80% of over 15-year-olds and more than 50 infected travellers can be allowed to enter without MIQ.

Effects of individual heterogeneity in probability of testing positive

Results for the model with individual heterogeneity in the probability of testing positive are provided in Supplementary Material. Overall, the effects of heterogeneity in probability of testing positive appear to be a relatively small part of the overall stochasticity of the simulation results. If there is heterogeneity between individuals in the probability of testing positive by LFT, this may decrease the performance of strategies based on daily LFT testing because some infected individuals can be missed, even when tested on five consecutive days. Further work is needed to more completely understand the sensitivity of the results to heterogeneity, but at this stage it appears to be a relatively small effect.

Mixed LFT and PCR strategy

Previous results suggest that, if we assume a high level of variability in LFT positivity, then two PCR tests taken on days 0 and 4 may be more effective at preventing undetected onward transmission than daily LFTs on days 0 to 4. This arises from the increased ability of a PCR test

to detect the virus later in the infection. This implies that a strategy of daily LFTs with a day 4 PCR may be best in reducing both onward transmission and undetected onward transmission.

We compare three scenarios: (1) the standard PCR on day 0 and 4, (2) the standard daily LFT for 5 days, and (3) a daily LFT on days 0 to 3 with a PCR test on day 4. When considering remaining transmission potential, strategy (1) is the worst option with 41% remaining. Strategies (2) and (3) are very similar, with around 23% of transmission potential remaining in both (for a vaccinated arrival that takes a pre-departure PCR test and enters a non-vaccinated population). This pattern holds when considering any onward transmission.

However, when comparing the probability of undetected onward transmission, the mixed testing strategy performs significantly better (1.2%) compared to the daily LFT (2.0%) and two PCR tests (4.0%). This suggests that, while the PCR test has a longer delay to returning results, the additional sensitivity later in infection when an individual is less likely to still transmit offsets this.

Discussion

We have modelled the effect of different border controls on the risk of international travellers infected with SARS-CoV-2 transmitting the virus and triggering community outbreaks. Potential border measures include a requirement for travellers to be vaccinated, different combinations of pre-departure testing and post-arrival testing and quarantine. We investigated outcomes at different levels of vaccine coverage in the domestic population.

Our results should be interpreted as estimates of the relative effectiveness of alternative mitigation strategies, rather than absolute predictions of risk. For example, the model estimates that pre-departure tests alone have a relatively small impact on the risk of a community outbreak. Adding post-arrival testing requirements provides a larger benefit and can cut the risk by around 50% relative to no testing. A further requirement for 5 days of self-isolation at home can cut the risk to around one third of the risk without mitigations. This

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result assumes that self-isolation is 40% effective in reducing transmission for asymptomatic or pre-symptomatic individuals and 80% effective for symptomatic individuals. The model results also clearly show the progressive reduction in risk as vaccine coverage in the domestic population increases: achieving 90% vaccine coverage amongst over-15-year-olds cuts the risk of a community outbreak by roughly a factor of 3.

Our results apply to the risks per infected traveller. The other key determinant of overall risk is the number of infected travellers, which is a product of the prevalence of infection amongst travellers and the travel volume. The latter variable is crucial because, while current travel volume is approximately 2,500 arrivals to New Zealand per week, this could increase substantially with the relaxation of travel eligibility and quarantine requirements. For example, a hypothetical scenario with 50,000 arrivals per week (i.e. around 50% of pre-pandemic travel volume) and a prevalence of 0.15 infections per 1000 travellers would mean around 7.5 infected arrivals per week. Under the more optimistic scenarios with high vaccine coverage and 5-day self-isolation and testing requirements , the model estimates the risk of a community outbreak to be in the region of 2% per infected arrival. This would translate to around one new community outbreak every 6-7 weeks.

If vaccine coverage is sufficiently high, the majority of these outbreaks may be stamped out with targeted measures like intensive community testing and contact tracing (Steyn et al 2021). However, this would likely require significantly higher capacity than has been used in previous outbreaks in New Zealand. In addition, some outbreaks would likely require broader interventions or even localised lockdowns, particularly if they affected population groups with relative low vaccine coverage or high contact rates. This suggests a staged approach to relaxing travel restrictions with a gradual as opposed to a sudden increase in travel volume, allowing case management and outbreak control systems to be tested.

The assumed reduction in transmission from individuals in self-isolation at home does not capture any specific effects, such as the increased relative likelihood of transmission to household contacts. Policies such as requiring all household contacts of self-isolating travellers to be vaccinated or mandating the collection of contact tracing information would further reduce risk. However, the effectiveness of home isolation is largely untested in the

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New Zealand context. Analysis of contact tracing data from March 2021 suggested that the introduction of a self-isolation requirement for international arrivals reduced transmission by 35% (James et al 2021), although this based on a small dataset that may not be representative of future cohorts of travellers.

Lateral flow rapid antigen tests have not previously been used in New Zealand. Trialling these alongside PCR tests in MIQ facilities and frontline border workers would allow for the collection of valuable real-world data to evaluate their sensitivity at different times relative to symptom onset.

The over-dispersed nature of SARS-CoV-2 transmission implies many infected people do not transmit the virus, or only infect one or two others, whereas a small minority of cases can infect a large number of other people. This means that, although the probability of an individual transmitting the virus may be low, the ones who do transmit can lead to outbreaks that grow faster than an average would suggest.

Including individual heterogeneity in the probability of testing positive by LFT can make strategies based on daily LFT testing slightly less effective than a two-test PCR strategy at reducing onward transmission from an undetected case. This indicates that there is some uncertainty as to the performance of the LFT strategy relative to the PCR strategy. Although the model results do not clearly favour the LFT-only strategy, they suggest that a daily LFT strategy with a PCR test on the final day could combine the best of both testing methods. This benefits from the high-frequency testing enabled by LFT, with a final PCR test giving an opportunity to detect cases who may have been missed by LFT.

We have assumed that vaccinated and non-vaccinated infected individuals have the same probability of developing symptoms of COVID-19. If in reality vaccinated infected people are less likely to develop symptoms, the effectiveness of post-arrival symptom checks and symptom-triggered testing in vaccinated travellers will be less than in the results shown here. However, this reduced effectiveness may be offset if likelihood of developing symptoms is correlated with infectiousness. Further work is needed to investigate this.

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Arrival Testing	Pre-Depart	Remaining Transmission Potential (Non-vaccinated Travellers)	Remaining Transmission Potential (Vaccinated Travellers)
Pre-departure Symptom Check Only		100%	50%
Regular Symptom Checks	No Test	77%	39%
	PCR on Day -3	76%	38%
	LFT on Day -1	73%	36%
PCR on days 0 & 4	No Test	66%	33%
	PCR on Day -3	65%	33%
	LFT on Day -1	63%	32%
Daily LFT for 5 days	No Test	45%	23%
	PCR on Day -3	45%	23%
	LFT on Day -1	44%	22%
5 day isolation + PCR on days 0 & 4	No Test	29%	15%
	PCR on Day -3	29%	14%
	LFT on Day -1	28%	14%
5 day isolation + Daily LFT for 5 days	No Test	20%	10%
	PCR on Day -3	20%	10%
	LFT on Day -1	20%	10%
7 Day MIQ + PCR on days 0 & 4	No Test	0.3%	0.2%
	PCR on Day -3	0.4%	0.2%
	LFT on Day -1	0.3%	0.2%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%

Table 2. Average remaining transmission potential of infected travellers under various border controls. All scenarios assume pre-departures symptom checks, regular post-arrival symptom checks, and symptom-triggered testing are implemented, with the exception of the first row.

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		Community vaccine coverage									
		Non-vaccinated travellers					Vaccinated travellers				
Arrival	**Pre-Depart**	**0%**	**60%**	**70%**	**80%**	**90%**	**0%**	**60%**	**70%**	**80%**	**90%**
No measures	Symptom check	26%	22%	21%	20%	19%	20%	17%	16%	15%	14%
Regular symptom checks	Symptom check	23%	20%	19%	18%	17%	18%	15%	14%	13%	12%
	PCR on day -3	22%	19%	19%	18%	17%	17%	14%	14%	13%	12%
	LFT on day -1	21%	18%	17%	16%	15%	16%	13%	13%	12%	11%
PCR on days 0 & 4	Symptom check	21%	18%	17%	16%	15%	16%	13%	12%	12%	11%
	PCR on day -3	21%	18%	17%	16%	15%	16%	13%	12%	11%	11%
	LFT on day -1	19%	16%	16%	15%	14%	15%	12%	12%	11%	10%
Daily LFT for 5 days	Symptom check	16%	13%	13%	12%	11%	12%	9.6%	9.0%	8.4%	7.7%
	PCR on day -3	16%	13%	13%	12%	11%	12%	9.5%	9.0%	8.3%	7.6%
	LFT on day -1	15%	13%	12%	11%	11%	11%	9.2%	8.7%	8.1%	7.4%
5 day isolation + PCR on days 0 & 4	Symptom check	15%	12%	12%	11%	10%	11%	8.3%	7.7%	7.0%	6.3%
	PCR on day -3	15%	12%	11%	11%	9.7%	10%	8.1%	7.5%	6.9%	6.2%
	LFT on day -1	14%	11%	11%	10%	9.3%	10%	7.8%	7.2%	6.6%	6.0%
5 day isolation + Daily LFT for 5 days	Symptom check	11%	8.9%	8.4%	7.8%	7.1%	7.6%	5.9%	5.4%	5.0%	4.5%
	PCR on day -3	11%	8.8%	8.3%	7.7%	7.0%	7.6%	5.8%	5.4%	4.9%	4.4%
	LFT on day -1	11%	8.5%	8.0%	7.5%	6.8%	7.3%	5.6%	5.2%	4.8%	4.3%
7 Day MIQ + PCR on days 0 & 4	Symptom check	0.4%	0.3%	0.3%	0.2%	0.2%	0.3%	0.2%	0.2%	0.1%	0.1%
	PCR on day -3	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%
	LFT on day -1	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%
14 Day MIQ + 2x PCR on days 3 and 12	Symptom check	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on day -3	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on day -1	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table 3. Probability of any onward local transmission from an infected traveller. Community vaccine coverage refers to the percentage of over 15-year-olds that are fully vaccinated in the community. All community vaccine coverage scenarios (except 0%) assume 90% of over 65-year-olds are fully vaccinated, with the remaining vaccinated individuals are distributed uniformly among the 15-64 year-olds.

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Non-vaccinated travellers						
		Community vaccine coverage				
Arrival	**Pre-Depart**	**0%**	**60%**	**70%**	**80%**	**90%**
Pre-departure Symptom Check Only		26%	22%	21%	20%	19%
Regular Symptom Checks	No Test	16%	13%	13%	12%	11%
	PCR on Day -3	15%	13%	12%	12%	11%
	LFT on Day -1	13%	12%	11%	11%	9.9%
PCR on days 0 & 4	No Test	3.2%	2.8%	2.7%	2.6%	2.4%
	PCR on Day -3	3.3%	2.9%	2.8%	2.6%	2.5%
	LFT on Day -1	3.2%	2.8%	2.7%	2.6%	2.5%
Daily LFT for 5 days	No Test	2.4%	2.1%	2.1%	2.0%	1.9%
	PCR on Day -3	2.3%	2.1%	2.0%	1.9%	1.8%
	LFT on Day -1	2.3%	2.1%	2.0%	1.9%	1.8%
5 day isolation + PCR on days 0 & 4	No Test	2.8%	2.3%	2.2%	2.1%	1.9%
	PCR on Day -3	2.6%	2.2%	2.1%	2.0%	1.9%
	LFT on Day -1	2.7%	2.3%	2.2%	2.0%	1.9%
5 day isolation + Daily LFT for 5 days	No Test	2.0%	1.7%	1.6%	1.6%	1.5%
	PCR on Day -3	2.0%	1.7%	1.6%	1.6%	1.5%
	LFT on Day -1	2.0%	1.7%	1.6%	1.5%	1.4%
7 Day MIQ + PCR on days 0 & 4	No Test	0.4%	0.3%	0.2%	0.2%	0.2%
	PCR on Day -3	0.4%	0.3%	0.3%	0.2%	0.2%
	LFT on Day -1	0.4%	0.3%	0.2%	0.2%	0.2%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%	0.0%	0.0%	0.0%

Vaccinated travellers						
		Community vaccine coverage				
		0%	**60%**	**70%**	**80%**	**90%**
No Symptom Checks		20%	17%	16%	15%	14%
Regular Symptom Checks	No Test	12%	9.7%	9.2%	8.6%	7.9%
	PCR on Day -3	12%	9.6%	9.0%	8.4%	7.8%
	LFT on Day -1	10%	8.6%	8.1%	7.6%	7.0%
PCR on days 0 & 4	No Test	2.7%	2.2%	2.1%	2.0%	1.8%
	PCR on Day -3	2.7%	2.2%	2.1%	2.0%	1.8%
	LFT on Day -1	2.8%	2.3%	2.2%	2.1%	1.9%
Daily LFT for 5 days	No Test	2.0%	1.7%	1.6%	1.5%	1.4%
	PCR on Day -3	1.9%	1.6%	1.6%	1.5%	1.4%
	LFT on Day -1	1.9%	1.6%	1.6%	1.5%	1.4%
5 day isolation + PCR on days 0 & 4	No Test	1.9%	1.5%	1.4%	1.3%	1.2%
	PCR on Day -3	2.0%	1.6%	1.5%	1.4%	1.2%

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	LFT on Day -1	1.8%	1.5%	1.4%	1.3%	1.2%
5 day isolation + Daily LFT for 5 days	No Test	1.5%	1.2%	1.2%	1.1%	1.0%
	PCR on Day -3	1.5%	1.2%	1.2%	1.1%	1.0%
	LFT on Day -1	1.5%	1.3%	1.2%	1.1%	1.0%
7 Day MIQ + PCR on days 0 & 4	No Test	0.2%	0.1%	0.1%	0.1%	0.1%
	PCR on Day -3	0.2%	0.1%	0.1%	0.1%	0.1%
	LFT on Day -1	0.2%	0.1%	0.1%	0.1%	0.1%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%	0.0%	0.0%	0.0%

Table 4. Probability of any onward transmission from an infected traveller who is never detected. Percentages 0%, 60%, 70%, 80%, and 90% refer to the percentage of over 15-year-olds that are vaccinated in the community. All scenarios except 0% assume 90% of over 65-year-olds are vaccinated, with the remaining doses distributed among the 15-64 year-olds.

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Vaccinated travellers						
		Community vaccine coverage				
		0%	60%	70%	80%	90%
Pre-departure Symptom Check Only		17%	13%	11%	9.4%	7.8%
Regular Symptom Checks	No Test	15%	10%	9.3%	7.9%	6.6%
	PCR on Day -3	14%	10%	8.7%	8.0%	6.3%
	LFT on Day -1	13%	9.7%	8.3%	7.3%	5.6%
PCR on days 0 & 4	No Test	13%	8.8%	8.1%	7.0%	5.5%
	PCR on Day -3	13%	8.9%	8.3%	6.6%	5.5%
	LFT on Day -1	12%	8.4%	7.8%	6.4%	5.0%
Daily LFT for 5 days	No Test	9.5%	6.6%	5.7%	4.8%	3.8%
	PCR on Day -3	9.2%	6.3%	5.9%	5.1%	3.9%
	LFT on Day -1	8.9%	6.1%	5.7%	4.7%	3.7%
5 day isolation + PCR on days 0 & 4	No Test	8.0%	5.2%	5.0%	3.6%	2.6%
	PCR on Day -3	7.7%	5.2%	4.4%	3.7%	2.7%
	LFT on Day -1	7.6%	4.8%	4.5%	3.4%	2.8%
5 day isolation + Daily LFT for 5 days	No Test	5.6%	3.7%	3.3%	2.5%	2.1%
	PCR on Day -3	5.7%	3.2%	3.0%	2.4%	1.9%
	LFT on Day -1	5.6%	3.7%	3.2%	2.4%	2.0%
7 Day MIQ + PCR on days 0 & 4	No Test	0.1%	0.1%	0.1%	0.1%	0.1%
	PCR on Day -3	0.1%	0.1%	0.1%	0.1%	0.0%
	LFT on Day -1	0.1%	0.1%	0.1%	0.1%	0.0%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%	0.0%	0.0%	0.0%

592 **Table 5.** Probability of an infected traveller starting an outbreak leading to at least 5
593 infections.
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Vaccinated travellers						
		Community vaccine coverage				
		0%	60%	70%	80%	90%
Pre-departure Symptom Check Only		17%	12%	9.7%	7.6%	5.5%
Regular Symptom Checks	No Test	15%	9.4%	8.3%	6.6%	4.4%
	PCR on Day -3	14%	9.5%	7.9%	6.6%	4.1%
	LFT on Day -1	13%	8.9%	7.4%	5.9%	3.8%
PCR on days 0 & 4	No Test	13%	8.2%	7.4%	5.8%	3.7%
	PCR on Day -3	12%	8.3%	7.4%	5.3%	3.9%
	LFT on Day -1	12%	7.7%	7.1%	5.3%	3.5%
Daily LFT for 5 days	No Test	9.4%	6.0%	5.1%	4.0%	2.8%
	PCR on Day -3	9.2%	5.9%	5.3%	4.2%	2.6%
	LFT on Day -1	8.7%	5.7%	5.2%	3.7%	2.5%
5 day isolation + PCR on days 0 & 4	No Test	7.9%	4.9%	4.5%	2.9%	1.7%
	PCR on Day -3	7.7%	5.0%	3.8%	3.1%	1.7%
	LFT on Day -1	7.4%	4.5%	4.0%	2.8%	1.9%
5 day isolation + Daily LFT for 5 days	No Test	5.5%	3.5%	2.9%	2.0%	1.6%
	PCR on Day -3	5.6%	3.1%	2.7%	2.0%	1.3%
	LFT on Day -1	5.6%	3.5%	3.0%	1.8%	1.4%
7 Day MIQ + PCR on days 0 & 4	No Test	0.1%	0.1%	0.1%	0.1%	0.1%
	PCR on Day -3	0.1%	0.0%	0.1%	0.1%	0.0%
	LFT on Day -1	0.1%	0.1%	0.0%	0.0%	0.0%
14 Day MIQ + 2x PCR on days 3 and 12	No Test	0.0%	0.0%	0.0%	0.0%	0.0%
	PCR on Day -3	0.0%	0.0%	0.0%	0.0%	0.0%
	LFT on Day -1	0.0%	0.0%	0.0%	0.0%	0.0%

595 **Table 6.** Probability of an infected traveller starting a large outbreak leading to at least 50
596 infections.
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Vaccinated travellers						
		Community vaccine coverage				
		0%	60%	70%	80%	90%
Pre-departure Symptom Check Only		6	9	10	13	18
Regular Symptom Checks	No Test	7	11	12	15	23
	PCR on Day -3	7	11	13	15	24
	LFT on Day -1	8	11	13	17	27
PCR on days 0 & 4	No Test	8	12	14	17	27
	PCR on Day -3	8	12	13	19	26
	LFT on Day -1	8	13	14	19	28
Daily LFT for 5 days	No Test	11	17	20	25	36
	PCR on Day -3	11	17	19	24	39
	LFT on Day -1	11	18	19	27	40
5 day isolation + PCR on days 0 & 4	No Test	13	21	22	35	58
	PCR on Day -3	13	20	27	33	59
	LFT on Day -1	13	22	25	36	52
5 day isolation + Daily LFT for 5 days	No Test	18	28	34	51	65
	PCR on Day -3	18	33	37	50	80
	LFT on Day -1	18	29	34	54	74
7 Day MIQ + PCR on days 0 & 4	No Test	769	769	1000	909	1000
	PCR on Day -3	1000	1000	1000	1000	1000
	LFT on Day -1	714	1000	1000	1000	1000
14 Day MIQ + 2x PCR on days 3 and 12	No Test	1000	1000	1000	1000	1000
	PCR on Day -3	1000	1000	1000	1000	1000
	LFT on Day -1	1000	1000	1000	1000	1000

598 **Table 7**. Expected number of infected travellers per large outbreak. Due to small numbers the
599 maximum size considered is 1,000 infected travellers. In many of these cases it is possible to
600 allow more.
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Visualising the effect of restrictions on travellers

The results in Table 2 of the main paper give the relative transmission potential of travellers under various restrictions, compared to a traveller that only faces a pre-departure symptom check. This “baseline” scenario is represented by the red curve in Figure S1. The relative transmission potential of an individual that also has a pre-departure PCR test and high symptom awareness post-arrival, for example, is given by the relative area under the purple curve to the area under the red curve.

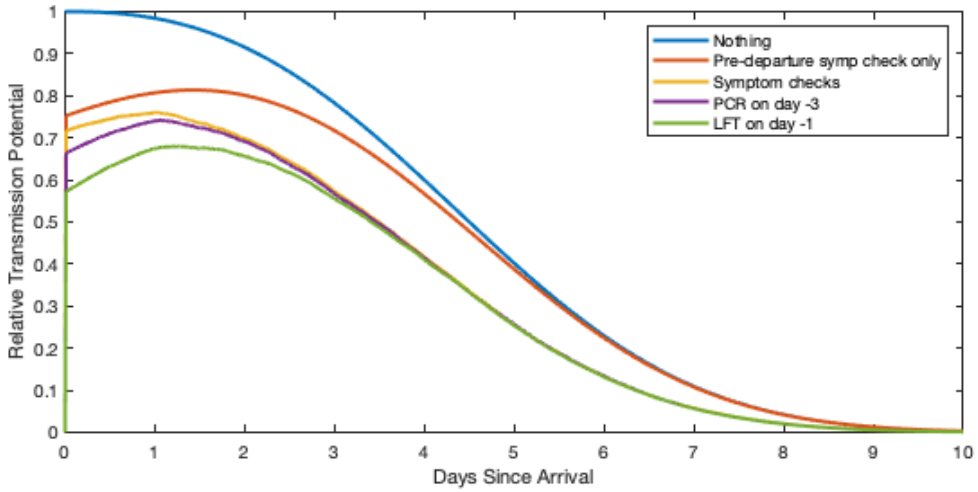


Figure S1. Relative infectiousness as a function of days since arrival. Control measures considered are all pre-departure only + post-arrival symptom awareness.

Implications of figure S1:

- Pre-departure symptom checks reduce risk the most in the first few days after arrival
    - In doing so they shift the peak risk (in the absence of other measures) to around 1.4 days after arrival
- Post-arrival symptom awareness noticeably reduces risk, especially from 2 days after arrival
- The addition of a PCR test 3 days prior to departure reduces transmission risk a small amount in the first day, but the effect is small
- A LFT on the day of departure has a greater effect than the PCR, and the benefit of this test also lasts longer. By day 4 there is no noticeable effect on risk from either.

Figure S2 considers additional testing and isolation measures.

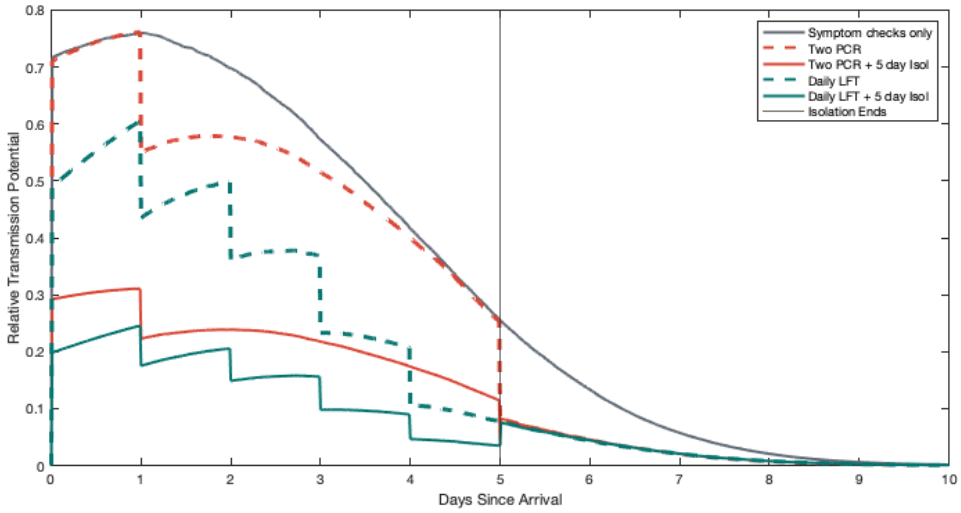


Figure S2. Relative infectiousness as a function of days since arrival.

Implications of figure S2:

- The 1-day delay in returning a day 0 (arrival) highly sensitive PCR test is **significantly** offset by the immediate results and isolation from a day 0 less sensitive LFT. Furthermore, the second LFT test on day 1 offsets the lower sensitivity.
    - A policy of isolation (or even MIQ) until results have been returned would remove a large amount of transmission potential in that first day.
- There is still a significant amount of transmission potential remaining after day 5.
    - Even if isolation was perfect (or 5 day MIQ was used) + either testing regime, a non-neglible amount of risk would remain
- The remaining transmission potential after the conclusion of the two testing regimes is about the same. This is a coincidence, but suggests that the *overall sensitivity* of the two testing regimes is estimated to be roughly equal.
    - Less surprisingly, as there is no interaction between tests & isolation strategy, the remaining transmission potential after someone finishes isolation is modelled to be the same as the remaining transmission potential of someone who never entered isolation.

Distribution of Secondary Cases from an Infected Traveller

[Caution: more trials are needed to decrease stochasticity of some of these results]

Tables S1 and S2 give the distribution of the number of secondary cases caused by an infected traveller under each policy. While increasing stringency of controls does decrease the likelihood of any outbreak (P>=1), there is still a chance of large outbreaks occurring even when self-isolation is required. This is because the modelled (heavy-tailed) individual heterogeneity in transmission is sufficiently large to counteract the (linear) reduction in transmission from isolation. **If restrictions meant that no individual had contact with this many people, then our model may be pessimistic.**

Policy	**P(0)**	**P(>=1)**	**P(>=2)**	**P(>=5)**	**P(>=10)**
Pre-departure symptom check only	83%	17%	10%	3.6%	0.94%
PCR on day 0 & 4	85%	15%	8.6%	3.0%	0.83%
5x LFT on days 0 to 4	89%	11%	6.2%	1.8%	0.5%
PCR on day 0 & 4, 5 day isolation	89%	11%	4.7%	0.78%	0.08%
5X LFT on days 0 to 4, 5 day isolation	93%	7.1%	2.9%	0.43%	0.08%

Table S1. Outbreak size distribution for each policy under **no domestic vaccination**

Policy	**P(0)**	**P(>=1)**	**P(>=2)**	**P(>=5)**	**P(>=10)**
Pre-departure symptom check only	88%	12%	5.3%	1.0%	0.09%
PCR on day 0 & 4	89%	11%	4.5%	0.81%	0.11%
5x LFT on days 0 to 4	93%	7.2%	2.9%	0.46%	0.04%
PCR on day 0 & 4, 5 day isolation	94%	6.1%	1.7%	0.15%	0.03%
5X LFT on days 0 to 4, 5 day isolation	96%	4.1%	1.1%	0.1%	0.01%

Table S2. Outbreak size distribution for each policy under **90% vaccination coverage of 15+ year-olds**

Implications of detecting infection in the traveller

Tables 3 & 4 in the main paper consider the probability that an infected traveller leads to any onward transmission, and any onward transmission where the traveller themselves are not detected. By detecting infection in the arriving traveller, even when onward transmission does occur, the traveller can be isolated faster and the contact tracing process can begin earlier. Table S3 gives the probability of a large outbreak occurring, conditional on whether the infected traveller was detected or not.

	-	No Vax		70% of 15+		90% of 15+	
	P(det)	Not	Det	Not	Det	Not	Det
Pre-departure symptom check only	0.68	28%	6.5%	16%	3.6%	8.6%	2.2%
PCR on day 0 & 4	0.94	33%	11%	18%	5.5%	9.1%	3.3%
5x LFT on days 0 to 4	0.94	29%	7.9%	14%	4.3%	7.8%	2.2%
PCR on day 0 & 4, 5 day isolation	0.94	23%	6.5%	11%	3.3%	5.9%	1.3%
5x LFT on days 0 to 4, 5 day isolation	0.94	19%	4.7%	10%	2.1%	5.2%	1.1%

Table S3. Probability of a large outbreak occurring conditional on whether the infected traveller was detected or not. Strategies ordered in increasing overall effectiveness.

There are two effects that may cause undetected travellers to pose greater risk:

1. A detected traveller is likely to be isolated earlier and is therefore less likely to cause any transmission
2. Detecting an outbreak in the traveller gives the contact tracing system a head start

Next steps: Quantify which of these two effects matters most, then link with local testing and contact tracing to get an idea of how important this is.

Time to Reach 50 Infections

Given a single seed case this can be calculated fairly trivially. Assuming R0 = 6.0 and no vaccination, it takes a median of 13 days (IQR 10, 17) to reach 50 infections (from exposure of the single seed case). With 70% coverage of over 15-year-olds it takes a median of 19 days (IQR 15, 25) to reach 50 infections. Finally, with 90% coverage of over 15-year-olds it takes a median of 23 days (IQR 18, 29) to reach 50 infections.

The above results assume that the outbreak is not detected in the arriving traveller. If we assume the contact tracing system kicks in on the same day as the seed case is exposed, in a non-vaccinated population the median increases slightly to 14 days (IQR 11, 18). The effect is also seen when 70% of over-15-year-olds are vaccinated (22 days, IQR 16, 28) and 90% of over 15-year-olds are vaccinated (24 days, IQR 18, 32).

The actual time to reach 50 infections will depend on the border policy to the extent that some policies result in different distributions of secondary cases from the arriving traveller. The temporal distribution of traveller's infectiousness will also play a role. That said, domestic vaccination levels and whether or not the outbreak was detected in the arriving traveller (allowing the contact tracing system to kick in early) are likely the two primary concerns.

Modelling different public health restrictions to manage COVID-19 as vaccine uptake grows

Purpose

The purpose of this note is to set out key areas of interest for modelling work that will support upcoming decisions about the approach to managing COVID-19 as vaccine coverage grows and border restrictions begin to reduce.

Context

Vaccination reduces (but does not eliminate) the health impacts of COVID and provides more flexibility to manage its effects. If high coverage is achieved, vaccination will enable a wider range of options to control outbreaks of COVID-19, with less frequent need to rely on strict mobility restrictions including 'lockdowns'. However, in New Zealand we don't have any quantitative understanding of the relationship between progress with the vaccine rollout and the 'sets' of public health and social measures that would be sufficient to control a resurgence (i.e. to reduce R0 <1).

In addition, we also do not know how these different approaches compare in terms of economic impacts. For example, even with a highly vaccinated population, some COVID resurgences are likely to need some level of mobility restrictions to manage. Stricter measures will more quickly control an outbreak, while low level restrictions will take longer to control an outbreak. Contact tracing is likely to be more effective at lower numbers of cases, suggesting that larger outbreaks would require more additional restrictions to control. It is also not clear which options have a larger economic cost when the population is highly vaccinated.

Objectives and benefits of this work

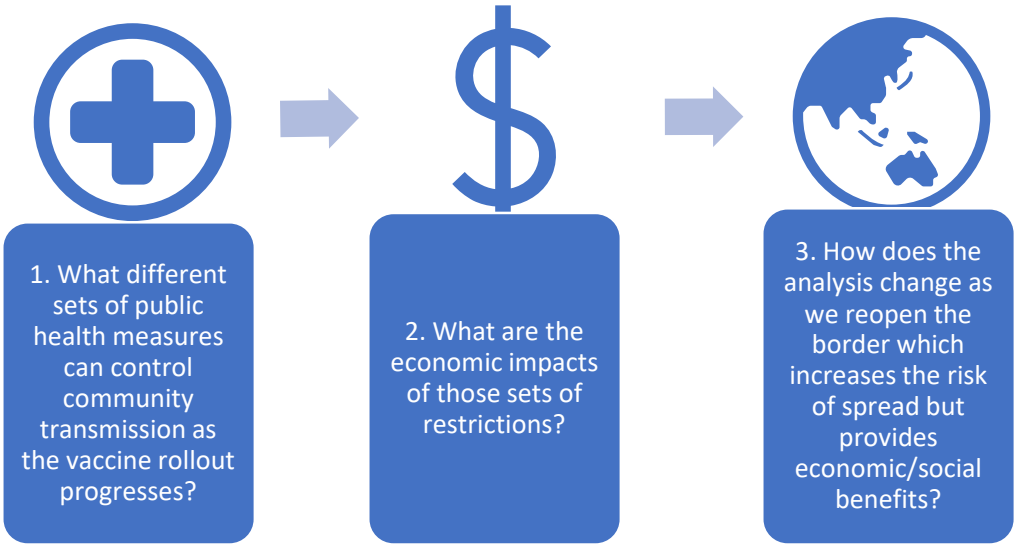
In broad terms we are seeking to answer the question: *what public health measures can effectively manage COVID-19 as the vaccine roll out progresses, and what are the health, border and economic impacts of those options?*

Scenario modelling work on this question would provide the following benefits:

- Support Cabinet decisions on management of the public health response in the later stages of the vaccine rollout and 'Reconnecting NZ' by providing a quantitative assessment of the risks and benefits of different COVID management choices over the medium term.
- Improve public understanding and support for the choices government may take around management of the public health response in the later stages of the vaccine rollout and Reconnecting NZ.
- Enable officials to be in a position advise on policy choices that will have significant public health and economic impacts.

General approach

There are three related questions to this modelling, summarised below. The attached table sets out in more detail the potential questions the modelling could examine, and links with existing work.



The Australian approach

A range of modelling in Australia has taken a scenario-based approach to understanding this relationship. Work by the Doherty Institute and Australian Treasury to support the Australian Government compares the impact of different levels of community vaccination, different management strategies and the bundles of public health measures to control an outbreak.

The strategies examined are broadly either, setting a binding constraint of not overwhelming the contact tracing system, and a (looser) binding constraint of not overwhelming hospital capacity. The former is similar to New Zealand's current 'elimination strategy' and the latter is something closer to a 'flattening the curve' approach where some level of community transmission is always present. A strategy of allowing cases to grow above hospital capacity was not modelled, as it was assumed that the economic and health costs of such a strategy would be too high.

The Australian Treasury then used the Doherty Institute's estimates of the length of time needed to contain the outbreak using bundles of more or less restrictive public health measures to assess the economic costs and compare the approaches. An assumption of 5 outbreaks per quarter is used, in line with Australian experience. They find that even with 70%+ of over 16s vaccinated, it is more cost effective to manage outbreaks by ensuring they do not exceed the capacity of contact tracing system, and with periodic low level restrictions (density and capacity constraints) rather than short but strict lockdowns. Keeping the contact tracing system working as effectively as possible, reduces the need for economically costly public health measures.

This work provides a potential basis and model structure to adapt for New Zealand. There are some key challenges to consider to applying it in a New Zealand context:

- Understanding transmission potential in NZ including how it changes with vaccination and the use of different public health restrictions.
- Considering what would make up a 'baseline' set of public health measures as there is no clear equivalent in NZ.
- Considering the effects on population sub-groups in NZ, as the modelling assumes uniform vaccine coverage and impacts.

Other work in Australia which could provide a model for NZ has also been undertaken by Professor Tony Blakeley (University of Melbourne), https://pursuit.unimelb.edu.au/articles/what-s-the-right-covid-19-risk-to-live-with and the Grattan Institute. https://grattan.edu.au/wp-content/uploads/2021/07/Race-to-80-our-best-shot-at-living-with-COVID-Grattan-Report.pdf

Key data/assumption needs

- Vaccine effectiveness assumptions, including reduction in infection, transmission, symptoms and impact from 'waning'
- Expected vaccination timing and age group structures
- NZ population mixing matrix
- Estimates of Reff across Alert Levels, and potentially with new bundles of interventions
- Estimates of effective capacity of contact tracing system, clinical capacity in hospitals
- Estimates of how the performance contact tracing reduces as more capacity is in use, and the impact on Reff
- Estimates of the frequency of outbreaks

Potential approach to modelling

	Module 1: As a greater proportion of the community is vaccinated, what are our options to manage community transmission?	*Module 2: … What are the economic impacts of these measures?*	*Module 3: How do our choices about reopening the border change these risks and costs?*
Questions to examine through modelling	• As the vaccine roll out progresses, what different sets of public health restrictions would control an outbreak (such that R_0<1) at key points in the vaccination roll out (e.g. 60%, 70%, 80% and 90% of over 12s)? • What are the public health impacts of those choices (e.g. hospitalisations and deaths)? • For what amount of time are these public health restrictions required to contain an outbreak? • How does this change if we rolled out the vaccinations to age groups under 12? • How does this analysis change if our binding constraint is the capacity of the contact tracing and testing system, or the hospital system? • How do different triggers for the use of population-wide restrictions change outcomes? E.g. any cases in the community, when cases are close to breaching contact tracing capacity or hospital system capacity? • What does further investment in the contact tracing and hospital capacity deliver?	• What are the economic impacts of the different bundles of public health restrictions that would control an outbreak at key points in the vaccination roll out? • Which mix of severity and length of public health restrictions at key points in the vaccination roll out creates the lowest economic impact? • What would be the impact of having some level of restrictions in place continuously?	• How do our conclusions in (1) change as we reopen the border in different ways? For example, is there a material difference in public health restrictions needed if a higher or lower risk reopening strategy is chosen? • What are the economic impacts from different border reopening options (both benefits and costs)?
Context and background	Te Pūnaha Matatini's vaccine model paper provides a starting point for this work, setting out the impacts of new COVID cases at different levels of community vaccination.	The Treasury's existing work to assess the impacts of Alert Level restrictions provides a basis for this work. We may need to estimate the economic effects of different 'bundles' of public health restrictions.	Te Pūnaha Matatini have modelled the relative risks of different types of border openings, which will be a key input for this work. There is also modelling under way to inform our understanding of 'traveller

	risk' which would inform our estimates of border risk.

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Subject:	RE: Agenda and papers for Friday"s Covid-19 Modelling Governance Group
Date:	Thursday, 28 October 2021 7:10:07 PM
Attachments:	image004.png 4558125_Summary of recent modelling insights and updates_v2.docx image002.png

Kia ora koutou – apologies for the late circulation. Attached is the paper for item 4 tomorrow.

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Subject: Agenda and papers for Friday's Covid-19 Modelling Governance Group

Kia ora koutou

Please find attached an agenda and papers for Friday, with the paper for item 4 to follow tomorrow.

Ngā mihi

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-
I do not work on Thursdays.
-

Summary of recent modelling insights and updates

28/10/2021

From: COVID-19 Modelling Steering Group

To: COVID-19 Modelling Governance Group

Purpose

This note summarises and consolidates findings and implications from a range of modelling outputs from TPM.

Also included in Annex 2 is a starter-for-ten on how DHBs could be assisted with the information needed for operational planning and decision-making needs at a local level.

What are the possible effects on transmission from school re-openings in Auckland?

TPM have modelled some scenarios of opening schools for all students, while otherwise continuing the level of community interventions (AL3, step 1), in Auckland if there are a small number of undetected cases in the community. The main findings are:

- Opening schools to all pupils increases opportunities for transmission within schools but also links households that wouldn't otherwise be linked, opening potential chains of transmission outside schools. The subsequent increase in infections occurs mainly due to transmission in other contexts, primarily close community contact outside of household bubbles, and cases within households. The *opportunity* for these transmissions is driven by the increase in connections between people as a result of opening the schools.
- Detected cases are similar with schools open to only the children of essential workers and open to all for the first week or so, but subsequently diverge. After two weeks, scenarios with schools open to all children have approximately twice the number of daily detected cases.
- In the scenario most consistent with current case growth, opening schools to all students would almost halve case doubling times from 10 days to around 5.5 days. This roughly corresponds to R(eff) increasing from 1.4 to 1.6.

A more detailed note is attached as Annex 1.

Vulnerable communities

The network contagion model (NCM) has been used to address the effects of unevenness of vaccination rates across different subpopulations on outbreak dynamics in an AL2 environment. Simulations show that higher vaccination rates imply slower growth in new cases, a longer time to detection of a new outbreak, fewer hospitalisations and more spread through younger age groups and schools.

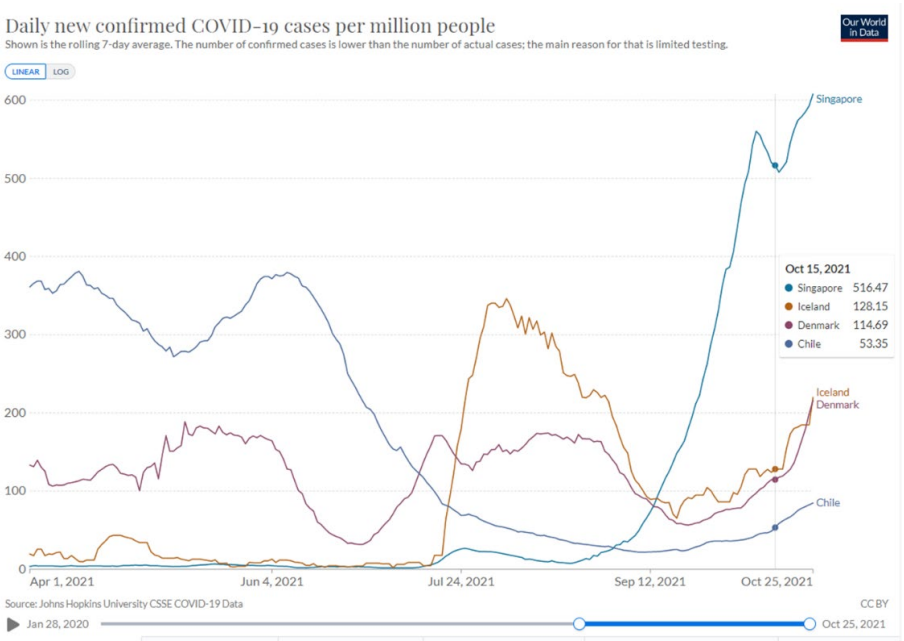
This has a range of interesting and perhaps counter-intuitive implications for testing strategies, for example a need for more surveillance testing in highly vaccinated communities, and looking at testing in schools as a leading indicator of case growth.

The relationship between cases and vaccinated populations

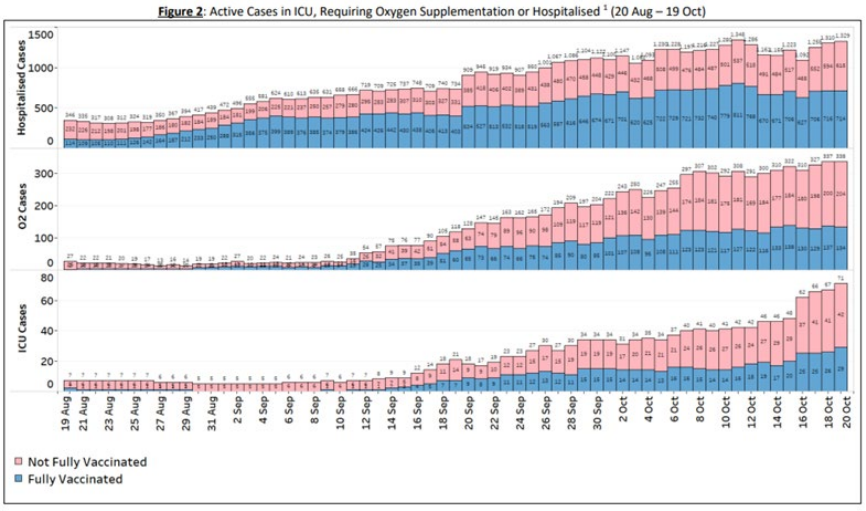
This is not strictly a modelling update, but we have noticed recent commentary suggesting vaccination will prevent rapid growth in case numbers. However it is important to remember that

exponential growth will still occur even in vaccinated populations so long as Reff>1. Vaccation will reduce the speed of this growth, and the absolute numbers infected but not prevent. This result is shown in earlier TPM modelling on the impact of allowing an epidemic to spread in an unconstrained manner in a highly vaccinated population. A related concern in these discussions is that exponential dynamics in transmission will be reflected in exponential dynamics for hospital admissions, under simple proportionality assumptions for severity. Because hospital capacity utilisation depends on duration of stay as well as rates of inflow, there is (yet another) complex non-linearity to account for when considering the implications of stochastic case projections for the likelihood of hitting hospital capacity constraints.

A good example of this is shown in the chart below, whereby countries with high vaccination rates are still experiencing significant case growth.



To further highlight the risks still present even with high levels of vaccination, it is informative to examine the situation in Singapore a little closer.



[1] Not fully vaccinated status includes persons who are partially vaccinated and completely unvaccinated.

The figure above shows that about half of the hospitalizations in Singapore are fully vaccinated. The overall **risk** of hospitalization for vaccinated people is significantly lower than otherwise. However, the volume of hospitalizations can still be high, and without other interventions has a very real risk of overwhelming the healthcare system.

What are the consequences of spread to AL2 regions?

The overall risk of new cases seeding outside of Auckland, where cases are by far the most prevalent, depends on the volume of active cases in Auckland and the leakiness of the various containment measures, including Auckland's AL3 border.

The risk of spread outside AL3 regions is a function of the number of movements (permitted and non-permitted) across the AL3 boundary. This risk is dependent on a range of factors compliance with the rules for movement, the individual-specific risk of the traveller, as well as who/how the AL3 contact interacts with others in the AL2 area. We do not have a modelled estimate of this risk.

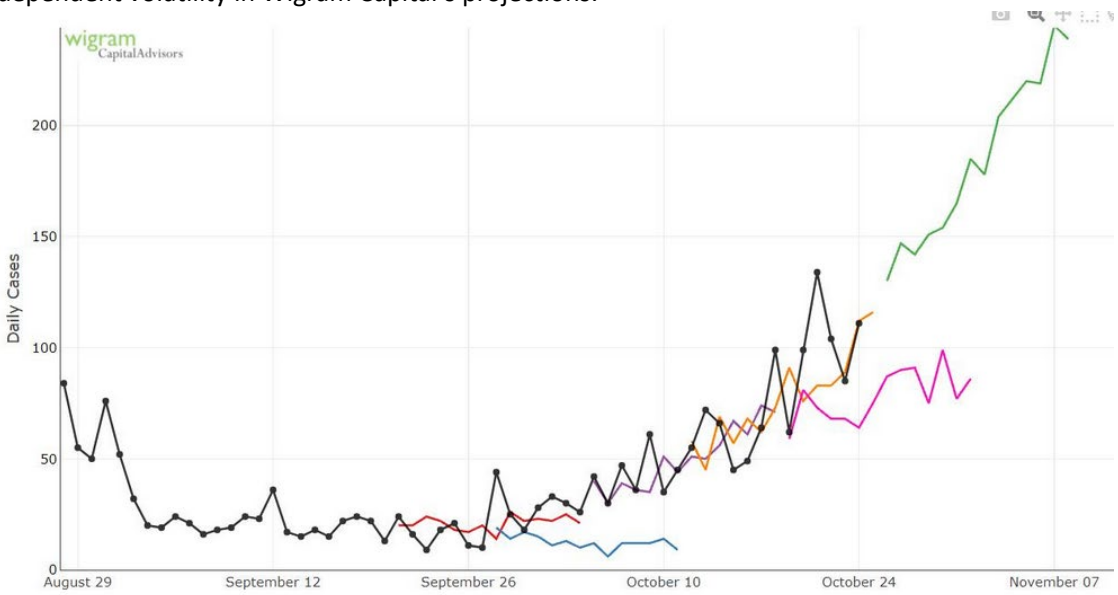
Previous modelling using the network contagion model (NCM) simulates outbreak dynamics in a seeding event given the contact network structure and the assumed likelihood of detection through symptomatic testing.

For example, if 20-40% of symptomatic people get tested, outbreaks would be (statistically) expected to be detected around 10 days after the seeding event, with an outbreak size (detected+undetected cases) at detection of around 40 total cases. Recent analysis of symptomatic testing rates suggests considerable heterogeneity across demographic groups.

Recent NCM analysis of the effect of opening schools demonstrates the highly non-linear effects (in part mediated by network dynamics) of different combinations of factors influencing the transmission environment. In a seeding event outside Auckland, these would include the local network characteristics around the seeding event (e.g. how connected is the index case) and the options across interventions and policy levers such as Alert Levels.

Wigram Capital

We continue to receive frequent case projections from Wigram for the current outbreak. They project 7-14 days ahead and provide estimates of Reff that can be compared against a range of other sources. This model has volatility and is sensitive to latest observed cases. When estimating Reff, stability is only achieved for estimates from about 10 days ago. Their current Reff estimates should therefore be treated with a great amount of caution. The plot below highlights the observed case dependent volatility in Wigram Capital's projections.



Wigram is also developing a SEIR model similar to TPM's to test the effect of different assumptions in the behaviour of infected individuals. We expect to receive results from this work in the next week and they plan to publicly release it in due course.

Annex 1: Impact of opening schools in Auckland while remaining otherwise at AL3

The Network Contagion Modelling team of Te Pūnaha Matatini have modelled some scenarios of opening schools for all students, while otherwise continuing the level of community interventions (AL3, step 1), in Auckland if there are a small number of undetected cases in the community. The main findings are:

- Opening schools to all pupils increases opportunities for transmission within schools but also links households that wouldn't otherwise be linked, opening potential chains of transmission outside schools. The subsequent increase in infections occurs mainly due to transmission in other contexts, primarily close community contact outside of household bubbles, and cases within households. The *opportunity* for these transmissions is driven by the increase in connections between people as a result of opening the schools.
- Detected cases are similar with schools open to only the children of essential workers and open to all for the first week or so, but subsequently diverge. After two weeks, scenarios with schools open to all children have approximately twice the number of daily detected cases.
- In the scenario most consistent with current case growth, opening schools to all students would almost halve case doubling times from 10 days to around 5.5 days. This roughly corresponds to R(eff) increasing from 1.4 to 1.6.

Detail

The NCM was parameterised with vaccine coverage and NPIs corresponding to early October 2021. The model includes the transmission reducing impact of partial vaccination, assumed to be half the rate of full vaccination. This model does not include R(eff) as a parameter but models its components directly. A range of values of the transmission rate parameter were used. Similar contact tracing parameters to those observed in August 2021 were used.

To model a scenario of AL3 step 1, with schools open to all children, the number of 'close' community (non-work, non-school) interactions are reduced by 50%. These interactions could include picnics and meeting outdoors – all community interactions are limited to a maximum of 10 people. For 'close' interactions that do occur, the model considers three scenarios for the reduction in transmission compared with AL1: 70%, 60% or 50% reduction. The more optimistic scenario (70% reduction) appears most consistent with recent case growth, though this may change over time.

Opening schools increases opportunities for transmission within schools, but critically, also links households that wouldn't otherwise be linked, opening potential chains of transmission outside schools. In the model simulations, while infections due to transmission in schools do occur, they are only around 10% of total infections; there is a larger increase in the number of infections due to transmission in other contexts (primarily within dwellings, and through community interactions). This indicates that while open schools themselves may not be where the majority of infections occur, they provide routes for transmission across previously unlinked communities. This then leads to significantly amplified volumes of infections within the community through transmission via close community contact, which happens more frequently at AL3.

Case numbers grow exponentially in all scenarios irrespective of schools' status, but opening schools reduces the doubling time for case numbers by around 35% to 45%. In a scenario with a case

doubling time of around 10 days, opening schools for all students would almost half this to 5.5 days. This roughly corresponds to R(eff) increasing from 1.4 to 1.6. This means within a month the number of doublings increases from 3 to over 5 doublings. At the end of the month, after 10 initial cases, that's the difference between approximately 80 new cases or 450 new cases.

Caveats

- The model considers opening schools for all primary and secondary students, not just those Year 11 to 13. The impact of opening to only Year 11 to 13 students will be lower, due to the smaller number of students affected and the potentially greater opportunity for distancing with fewer students on site. Year 11 to 13 students account for roughly 20% of all students in Auckland.
- Parameter uncertainties mean that the absolute case numbers in the modelled scenarios may not be reliable, but the relative effect of opening schools to all pupils vs only children of essential workers seem to be robust to a range of parameter values.
- Contact tracing speed reflects that in week 1 of the August 2021 outbreak.
- The impact of AL3 step 1 on transmission in community interactions is uncertain. If almost all community interactions are outside, masked, and distanced, the reduction in transmission compared with AL1 may be underestimated in the model. Current case growth is more consistent with the more optimistic scenario considered (a 70% reduction in transmission per interaction). Future case and contact data will provide more information about the actual impact.

Annex 2: Information for operational planning and decision-making needs at a DHB level

There is currently an information gap in data, modelled projections and possible future scenarios that is required by operational agencies, and particularly by DHBs to assist in their readiness for outbreaks of COVID-19 throughout the country, associated with the shift in strategy for dealing with the pandemic domestically.

There is a risk each of the DHBs making up their own scenarios/assumptions that are not necessarily aligned with each other, or anything that's being centrally used to plan capacities, contingencies, and the like.

It may be worth discussing as officials, then putting some suggestions through to TPM about some standard resources they could provide. Namely:

- Future (1 year horizon say) scenarios based on the latest iteration of the SEIR models
    - The relevant outputs can be broken down daily, which will allow for aggregation as desired by the user
    - Different intervention assumptions can be easily implemented
    - Ideally, do we want to make this available as a service so the DHB's and others can run a set of scenarios by changing assumptions within some pre-set parameter spaces,
    - Operational dashboard(s), currently in development should run off these numbers at the very least
- Restart the ability to run the BPM as a short forecasting tool (or for bespoke scenarios in the 2 - 3 month domain, including outbreak dynamics)
    - The ability to run these at a DHB level can be restored
    - Perhaps a service like what Orion Health provided in 2020?
- Extract the connection network from the NCM, and allow users to test different connectivity/intervention assumptions across this
    - The actual spread dynamics need not be modelled, as the relative change in risk can still be established by examining the topology of the networks themselves
    - If this is presented in a sensible way, it could be a supplementary risk assessment tool in terms of interventions (particularly as we move to geography specific restrictions).

On top of that, any level of risk forecasting we could do may also be useful for operational purposes. As the outbreak grows, we may enter the realm of needing as early a warning system as possible in terms of surge preparations and healthcare capacity limits being approached.

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Cc: ^EXT: Talosaga Talosaga; xxxx.xxxx@xxxxxx.xxxx; Rubudu Senanayake; Christopher Nees [TSY]; Harry Nicholls [TSY]; Patricia Priest; Alice Hume [DPMC]
Subject: FW: COVID strategy modelling catch up [Draft strategy and scenarios document]
Date: Thursday, 16 September 2021 12:58:22 PM
Attachments: image001.png
Modelling scenario strategies 1200 Thurs.docx

Hello Modelling Governance Group

I wanted to share with you the working draft for the scope of the next round of significant modelling work which primarily relates to our ongoing work with the TPM teams. This is the piece that will produce Doherty Institute or UoM/Blakeley -esque results for New Zealand, and as we discussed at the previous Governance Group discussion.

You'll note this is incomplete and has plenty of comments: this is a vehicle for documenting the conversations we have had in the Steering Group and for recording and iterating discussion with the TPM researchers. We have our next catchup with them tomorrow afternoon, as below.

Despite that, if you do have reactions at this time about the nature of the work (the strategies that we are outlining, the outcomes which they relate to, and the arrangement of "rules" which assemble to deliver these) then we'd be very happy to hear those and incorporate as the project progresses.

Some process points:

- We have arranged for regular weekly check-ins with Minister Verrall where Chris, Trish and I will update her on progress and deliverables over the next 1-2 months.
- I suggest that we also share the scoping document with Professor Skegg, but I will do that with a version from early next week which captures tomorrow's discussion with TPM and is much cleaner in terms of number of comments
- Trish will share with other colleagues in the Ministry who will be interested in being sighted on/inputting to this work at an early stage.

Thanks

George

George Whitworth
Principal Policy Advisor, COVID-19 Group
Department of the Prime Minister and Cabinet

P + s9(2)(g)(ii)
E xx@xx

From: George Whitworth [DPMC]
Sent: Thursday, 16 September 2021 12:43 pm
To: Christopher Nees [TSY] <xxxxx.xxxx@xxxxxxxx.xxxx.xx>; Patricia Priest <xxxxxxxx.xxxxxx@xxxxxx.xxxx.xx>; Pubudu Senanayake <Pubudu.Senanayake@stats.govt.nz>; ^EXT: Talosaga Talosaga <xxxxxxxx.xxxxxxxx@xxxxxx.xxxx.xx>; Harry Nicholls [TSY] <xxxxx.xxxxxxxx@xxxxxxxx.xxxx.xx>; xxxxx.xxxxx@xxxxxxxx.xx.xx; Dion O'Neale <x.xxxxxx@xxxxxxxx.xx.xx>; Emily Harvey <xxxxx@xx.xx.xx>; Patricia Priest <xxxxxxxx.xxxxxx@xxxxx.xx.xx>; Michael Plank <michael.plank@canterbury.ac.nz>
Cc: Tim Ng [TSY] <xxx.xx@xxxxxxxx.xxxx.xx>; Hemant Passi [TSY] <xxxxxx.xxxxx@xxxxxxxx.xxxx.xx>; pmcsa <xxxxx@xxxxxxxx.xx.xx>; Pippa Scott <xxxxx.xxxxx@xxxxxx.xxxx.xx>; Oliver Maclaren <oliver.maclaren@auckland.ac.nz>; Nicholas Steyn <xxxxxxxx.xxxxx@xxxxxxxx.xx.xx>
Subject: RE: COVID strategy modelling catch up [Draft strategy and scenarios document]

[UNCLASSIFIED]

Hi all

With thanks to my colleagues on the steering group for iterating thinking over multiple versions, I've attached a document which aims to crystallise the commissioning around this next chunk of COVID-19 strategy modelling. This should be consistent with our conversations to date, with the rough and ready work that the BPM team had been producing, and hopefully progresses thinking on some of the goalposts in whatever sport it is we are playing.

This document also about documenting our thinking and sharing it with less engaged colleagues. On that basis, there are a bunch of unresolved comments, and the content of pages 1,2,3 will be pretty familiar to this group. You will likely want to commit a little more attention to 4,5,6.

In terms of what it would be good to achieve at tomorrow's catchup:

- Discussion on the question of "rules-based outcomes" vs "outcomes-based rules", whether both are useful in different ways, and whether it makes sense to do one ahead of the other.
- Agreement on a small number of initial scenarios (strategies x assumptions) with defined rules for some initial modelling results in the near-term.
- Discussion of what we can expect from the BPM and NCM teams in relation to this work, and in particular whether there are outputs of the NCM that can help inform the BPM, and when we can expect it.

Very happy to discuss, as ever.

George

George Whitworth
Principal Policy Advisor, COVID-19 Group
Department of the Prime Minister and Cabinet

P +s9(2)(g)(ii)
E xx@xxx

Strategies, scenarios and decision rules

There are four key domains for managing COVID-19. Vaccinations are a foundation. The other three can be dynamically reorganised, reacting to conditions.

- Vaccinations;
- Domestic restrictions (for which we can use the existing Alert Level for simplicity, noting these may change in future);
- Test, trace, isolate and quarantine (TTIQ) requirements; and
- Border controls.

A strategy is a set of rules determining when/how these tools are deployed in order to meet a given objective. Interested in three high-level strategies:

A	Strict Elimination	Minimise imported cases and maintain a strict "stamp it out" approach whenever cases are detected.	*Allows us to explore how much domestic risk is reduced / more open borders could be at higher rates of vaccination.*
B	Tight Suppression	Higher tolerance for imported cases than (A), but at a rate which does not overwhelm contact tracing capacities.	*Allows us to explore how continuous but sustainable detection and suppression of clusters might be managed.*
C	Loose Suppression	Keeping the burden of infection within hospital system capacity, not crowding out other health services.	*Allows us to understand thresholds in health system and calibrate rules based on lag times to avoid "overshoot".*

Each *strategy* will be compared across multiple *scenarios* to capture permutations of vaccination coverage, border settings and domestic restrictions.

Purpose: Informing strategy vs capacity planning?

1. Informing strategy into 2022 and beyond: Modelling the impact of high-level strategies (strict elimination, keeping cases within contact tracing (CT) capacity, keeping cases within hospital capacity). Are there 'win-win' strategies that improve health and reduce need for AL use? Is there a "least-cost" approach for which the hospital capacity is the relevant binding constraint?
2. Capacity planning: Modelling the health system impacts of reopening scenarios (use of CT, testing, primary care, MIQ for domestic cases, hospital, ICU, etc.). This is to inform where investments are made and to inform understanding of lead-in times for different strategies.

The two are interrelated, but can be sequenced to prioritise the first, with the second to follow:

- The first could be answered with relatively high-level modelling, since it is to inform high-level strategic decisions. We need to remain mindful that, at this level, marginal differences in modelled outcomes across potential strategies will not give us confidence that one is necessarily better than the other. It may be that one strategy is a clear winner across multiple (health + other) dimensions, or else the 'right' strategy will be a value judgement where model results can help to inform decisions around trade-offs but ultimately only get you so far. This lends itself to 'wide' sensitivity analysis: see if results are robust to significant changes to key variables, avoid getting hung up on precise estimates if high uncertainty.
- The second question requires quite detailed modelling. This will include detail on processes (e.g. capacity for different parts of the CT process, what are the flows inside and between hospitals), detail on geographic distribution (e.g. no point building ICU capacity in Christchurch if most cases will be in Auckland), details on vaccine coverage gaps (which depend on how the rollout goes) and iteration between officials, modellers and subject matter experts / 'owners' of public health and health system functions.

Commented [GW[1]: These tools are intended to reduce one of the following:
- Number of infectious arrivals
- Chance that infectious arrival evades detection at the border, and/or transmits infection
- Time to detection for new cases (either in recent arrivals, or in the wider community)
- Reducing the size of the outbreak at detection
- Reducing transmission (Reff/k) between known cases and the wider community (which, in turn, buttresses contact tracing/testing efforts)

Commented [GW[2]: IL comment: Need to think about boosters adding a dynamic element to vaccination state.

Commented [GW[3]: Q: We can define the strategies in terms of the hypothetical rules that might be consistent with the strategy. Or we can use the modelling to guide us in terms of optimal decision rules for a given strategic objective. Which do we prefer? Would we want both?

Commented [GW[4]: Unclear whether there is a realistic/feasible/desirable set of measures which deliver this outcome

Commented [GW[5R4]: MS comment: can we model what theoretical CT capacity we would need to maintain to sustainably deliver this strategy?

Commented [GW[6]: Open question whether there is a difference between B and C (or, put another way, unclear whether there are scenarios where contact tracing/testing capacity is overwhelmed but the hospital system is not, at a later point, without mitigating population level controls being deployed)

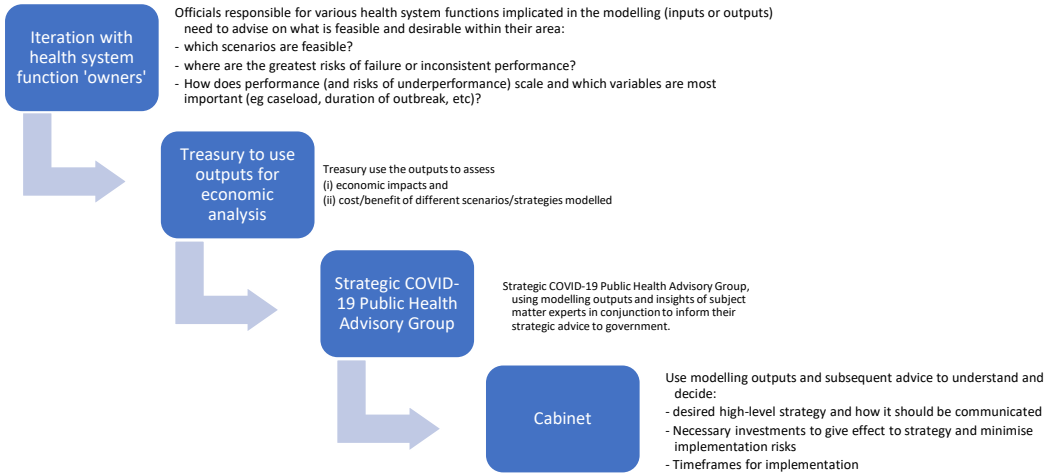
Commented [GW[7R6]: IL comment: Is there a scenario where a least cost approach would result in keeping hospital below capacity?

...

Outputs for comparison across strategies and scenarios

1. (for health system planning, per AC note) Total number of cases per day as COVID spreads (by region and nationally). Of which:
    a. Number requiring admission to hospital and expected length of stay
    b. Number requiring Intensive Care and expected length of stay
2. Time at each level of restrictions
3. Time spent "breaching" CT capacity
4. Infectious arrivals imported over time – analysis of "how many is too many" and in which scenarios imported cases matter more/less
5. Number of contacts over time, number of people tested, number of people required to isolate (e.g. the UK's pingdemic)

What will we do with the outputs?



Subsequent outputs

- Want to be able to add additional functions or complexity afterwards (eg new strategy features, etc)
- Can we model "top-down"? What are the optimal decision rules if we don't want to over-run health system capacity but allow the model to optimise for minimum economic impact. (when – how long is the lag? How strong is the response? TO what – how many eg new cases?)

Commented [GW[8]: TT comment:
•**Capacity as a model input or model output?** I think as a practical matter, we'll need to pick some starting values and iterate as we talk with relevant groups. For example, the ICU folks are asking us how many ICU beds they should be planning for when the border opens. There's a 'chicken and egg' problem between planning capacity and planning the 'level of reopening'.

Commented [GW[9R8]: Agree – think we should approach this from both sides:
-Is a strategy/scenario deliverable within current system capacities?
-What capacity level or performance standard would be required for a strategy to be deliverable in a given scenario?

Commented [GW[10R8]: •stratified by age band and vaccination status

Commented [GW[11]: Is this likely to be synonymous with time where AL3/4 is required? I guess an output that relates to CT capacity usage over time would be instructive, even if in some scenarios this is locked at 100% for long periods (~broken)

Commented [GW[12]: NB: Likely interest in questions about transitioning between strategies. For example:
•Can we go back to A or B, from C, and at what cost?
•What does a gradual transition from A to C look like?

Required Inputs

1. Time series for imported cases
    a. which may be a function of border settings, and so may be reactive to conditions under different scenarios
    b. which will, at some point, become a less relevant factor if a return to zero is not envisaged in a particular scenario(?)

2. System performance/capacity parameters (current & feasible future, needs to be real):
    a. Contact tracing operations and performance (# cases/day; #contacts/day; peak active cases/contacts). Calibrated as a function of:
        i. Concurrent population level restrictions (Alert Levels)
        ii. Case load
    b. Hospital system capacity
        i. Baseline/generalised load: community care and GPs, flow on impacts
        ii. Hospitalisations and wards, geographic distribution
        iii. ICU/HDU capacity, geographic distribution/assumptions
    c. Testing (PCR, other types of test?) (#'screening' tests/day, #'surveillance' tests/day)
    d. Surveillance (chance of detection in recent arrivals, size of cluster in the community at detection, duration from seed to detection)
        i. Estimated rate of testing in symptomatic population
        ii. *CN: Because of high vaccination rates and the likelihood of testing only if symptomatic, assume a delay of one week/second generation detection We may want to do future sensitivity testing around that later. (TP comment: I think this is pretty optimistic – this current outbreak was not detected for 10 days after the first border case, if we believe the narrative, and that's with people being symptomatic?).*
    e. Alert Level controls / other population restrictions/requirements:
        i. Expectations around compliance with public health measures (eg isolation requirements) and population restrictions
        ii. Estimated impacts of switching on different interventions

3. Vaccination rates – which rates/distributions do we expect? Which are we comfortable explicitly exploring in each scenario?

4. "Coherent" scenarios. Dimensions: border openness, vaccination coverage, tolerated case-loads/restrictiveness

See Back page for a list of assumptions in recent BPM straw-scenarios

Commented [GW[13]: NB: Talo was going to have a think about building this out and systematically capturing the different modules. Some of this might be for future iterations rather than necessary through the first half of this body of work.

Commented [GW[14]: Link to Richard A et al work. (Pubudu: We can also use the Canadian Defence Research group's work.(?))

Commented [GW[15]: Interested in where the network model can be used to model effectiveness of different interventions to validate or estimate inputs to the BPM

Commented [GW[16]: CN: The Roche review last year suggested this was 500 contacts a day , surging to ...

Commented [GW[17R16]: From Blakeley/UoM: We have put extensive effort into calibrating contact tracing in the model so that: ...

Commented [GW[18R16]: IL comment: How easily can we use tech to change this. Can Bluetooth settings be tweaked? Have other countries had success with Bluetooth?

Commented [GW[19]: IL comment: Is it worth building in scenarios around changes in severity of disease, either due to variants, or new treatments?

Commented [GW[20]: Pubudu: Also incorporate testing without isolation as a potential setting in some scenarios, or if quarantine capacity breached?

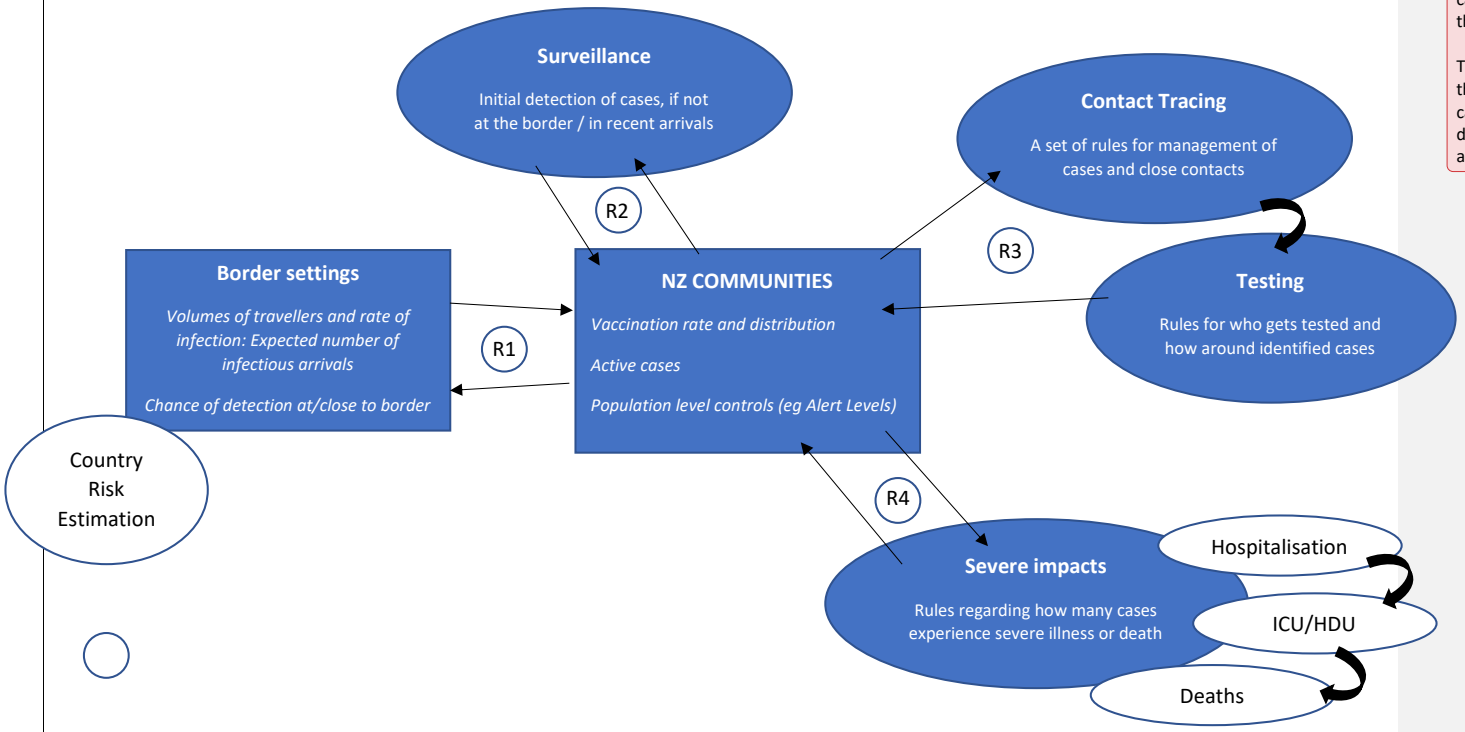
Commented [GW[21]: TP comment: need to envisage a world where there is a level of routine testing – could be of random samples of the population, could be of particular ...

Commented [GW[22]: Need to be explicit, and careful, about how interventions are modelled (proportional ...

Commented [GW[23]: Pubudu: hypothetical worst case scenarios? EG spread in communities with low vaccination uptake? Explore whether we can expedite linking extra dat ...

Strategy maps

Strategy	A. Strict Elimination	B. Tight Suppression	C. Loose Suppression
Objectives	Minimise imported cases and maintain a strict "stamp it out" approach whenever cases are detected.	Higher tolerance for imported cases than (A), but at a rate which does not overwhelm contact tracing capacities.	Keeping the burden of infection within hospital system capacity, not crowding out other health services.



Commented [GW[24]: Need to add case management system: rules for adding cases to quarantine, ensuring we capture MIQ constraints, or agreement in which strategies this remains a feature that needs to be understood.

TT comment: "decision rule should respond more to cases that suggest there is unobserved community spread (i.e. cases with no clear link to the border)." – suggestive of different systems for testing vs surveillance and different R2 and R3 mechanisms.

Strategy rule table

Strategy	A. Strict Elimination	B. Tight Suppression	C. Loose Suppression
Objectives	Minimise imported cases and maintain a strict "stamp it out" approach whenever cases are detected.	Higher tolerance for imported cases than (A), but at a rate which does not overwhelm contact tracing capacities.	Keeping the burden of infection within hospital system capacity, not crowding out other health services.
Baseline population interventions	[Specify] eg 'baseline settings' always on (ongoing masking rules, home testing, surveillance methods)	[Specify – may be the same across all. We may want scenarios with different baselines: a "baseline", "baseline+" and an "AL2 baseline"]	[Specify]
Decision rules			
R1 ***Border Settings***	**Escalation:** Restricting flows of higher-risk travels. For example, saying that certain travellers must do a 7-day MIQ instead of a self-testing regime, or 14-MIQ instead of 7. Real world: many practical constraints on speed (so we should assume lagged effect to measures) and a reluctance to bounce up and down a lot (so this lever should only get pulled where (i) circumstances are severe and (ii) restricting imported cases makes a difference to outcomes. **De-escalation:** Scenarios could assume a steady increase in the number of infectious arrivals allowed while other conditions remain within defined boun		
	A very gradual increase in risk at the border and quick to snap-back under adverse outcomes.		*More risk at the border may be tolerated for longe and any retrenchment less severe.*
R2 ***Surveillance outcomes and initial case detection***	**Escalation:** - On first detection, raise Alert Levels to [AL2] - >5 cases/week from 'surveillance' tests → raise Alert Levels to [AL3]. **De-escalation:** conditional on <1 case per day arising from "surveillance" testing.	**Escalation:** - First detection, no AL shift, full capacity contact tracing (max effectiveness, subject to R3). - If >10 "surveillance" cases/day, then raise Alert Levels **De-escalation:** conditional on <1 case per day arising from "surveillance" testing.	**Escalation:** no conditionality on 'surveillance' detections **De-escalation:** no conditionality on 'surveillance' detections
R3 ***Test, Trace, Isolate & Quarantine***	**Escalation:** - Any cases: Full capacity contact tracing - Contact tracing should be explicitly modelled as much more effective at very low case numbers.	**Escalation:** - Any cases: Full capacity contact tracing - Contact tracing should be explicitly modelled as much more effective at very low case numbers.	**Escalation:** - Any cases: full capacity contact tracing (w significantly lower effectiveness as case numbers increase) - No response if capacities exceeded. **De-escalation:** N/A

Commented [GW[25]: PS comment: I think we need a way of categorizing outbreaks. For example, a case emerging in a community that is say 90% vaccinated is probably less of a concern compared to that in a community with 40% vaccination. The reaction functions therefore may need to be fine tuned with PH expertise. For example if we are seeing 10 cases a day in a highly vaccinated community, is the reaction going to be the same as seeing that in a community with very low vaccination rates?

Commented [GW[26R25]: TP comment: Reff not a useful indicator for decision-making in small outbreaks, or early in outbreaks. How useful can Reff be with multiple concurrent outbreaks?

Commented [GW[27]: Need to add case management system: rules for adding cases to quarantine, or agreement in which strategies this remains a feature that needs to be understood.

TT comment: "decision rule should respond more to cases that suggest there is unobserved community spread (i.e. cases with no clear link to the border)." – suggestive of different systems for testing vs surveillance and different R2 and R3 mechanisms.

Commented [GW[28]: Initial work: three scenarios in each strategy?
no border changes, or redistribute travellers such that it reduces the risk of transmission (combination of a reduced number of travellers and reducing the probability that they will cause onward transmission / cause an outbreak) by 25% and 50%.

Commented [GW[29]: We may need some "AND" conditionality between R2 and R3 – active cases AND new detections draws a greater response than just one or the other.

Commented [GW[30R29]: Compare scenarios under this strategy for straight to AL2 vs straight to AL3 reactions – test: relative time required to re-eliminate.

	- Simplify: Active cases does not breach quarantine capacity. **De-escalation:** - Reduce AL3 to AL2 if… - Reduce AL2 to baseline if…	- Active cases may breach quarantine capacity → degrading reduction in onward transmission - Alert Levels: Scenarios to compare turning on AL2 and AL3 when cases grow to [>90%] of CT capacity (to simulate scenario where we may breach this capacity for a short period but we can still bring it back under control.) **De-escalation:** - Contact tracing performance improves as case numbers decrease - AL level is reduced when case loads <[threshold % theoretical CT capacity]	
R4 ***Hospital system outcomes***	**Escalation/De-escalation:** - Simplify: assume no escalation based on hospital system in this scenario (because burdens maintained at relatively low level.	**Escalation:** - [Need escalation condition for increasing hospital capacity as that is implication that "CT first" strategy is not working.] **De-escalation:** - [Then need related de-escalation condition]	**Escalation:** - Turn on [AL2/AL3] when cases [>60%/>80 of "sustainable" ICU OR ward capacity reached. **De-escalation:** - Reduce AL3 to AL2 when ICU AND ward capacity [<60%] AND Reff <1 - Reduce AL2 to baseline when ICU AND wa capacity [<40%] AND Reff <1

Commented [GW[31]: TP comment:
Issues with estimating Reff when numbers get low – what about (for elimination) a certain number of days with 0 cases, and for others a certain number of days with cases<X?

Commented [PP32]: I think this threshold is too high – the lag between increasing ALs and reducing contacts would mean (I think?) that under this assumption CT capacity would be breached by quite a lot and therefore potentially not for just a short period?

Commented [GW[33]: Need to set thresholds that ensure we have high confidence we do not exceed total capacity, despite lag times between Alert Level choices and hospitalisation outcomes.

Commented [GW[34]: [Evidence suggested] current ICU capacity ~350 beds nationally. So need to decide what's a 'reasonable estimate' of the capacity to manage covid cases for now. Assume there isn't much/any spare capacity and that any beds used by COVID patients ultimately mean electives more likely to be cancelled (TP comment: If we're modelling for the medium term, we have to have electives not being cancelled – i.e. 'bau' COVID use would largely need to be on top of current capacity?) or surge capacity is brought on line.

[References]

- UoM/Blakeley Pandemic Trade-offs work mostly based on rules related to new cases per day.
    - https://populationinterventions.science.unimelb.edu.au/pandemic-trade-offs-detail-july-2021/
    - Whether it uses per million vs absolute numbers of cases depends on which strategy. Full details here: https://populationinterventions.science.unimelb.edu.au/posts/pandemic-trade-offs-detail/doc-strategies.pdf

[BPM model assumptions]

- Starting value of R0=4.5 in a fully susceptible population, representing Delta variant with baselines PHSM, e.g. masks, ventilation, indoor density or gathering size limits, working from home
- Reff reduced by an additional:
    - 25% at level 2 - sufficient for control if Rv<1.33
    - 50% at level 3 – sufficient for control if Rv<2
    - 75% at level 4 – sufficient for control if Rv<4
    - Could use the network model to get better estimates for these parameters?
    - Doherty PHSM assumptions look similar (24% low, 40% medium, 60% high)
- Vaccine coverage (% 1st dose, % 2nd dose) in 5-year age bands
- Vaccine effectiveness = baseline assumptions from vaccination model paper, no waning immunity
- Number of seed cases per unit time and any testing, quarantine or vaccination requirements. For now I'm assuming seed cases are unvaccinated and have no special requirements, this will be roughly equivalent to a higher number of mitigated seed cases.
- Trigger to raise/lower alert level:
    - More than 500 active detected cases
    - More than 500 occupied hospital beds
    - Use the lowest alert level required to get R<1
    - Reduce alert level when the trigger variable falls to 20% of the threshold
- Proportion of symptomatic infections who get tested = 20%
- Mean time from onset to test = 4 days
- Effectiveness of case isolation = 100%
- Proportion of contacts of confirmed cases traced = 70%
- Mean time from confirmation of index case to quarantine of contacts = 3 days

Commented [PP35]: I think if the starting value is a fully susceptible population it should also represent no PHSM – then the effect of those is explicitly modelled. If R0 is 6 for delta, do we know that Reff would be 4.5 with masks, ventilation etc? Using this assumption prevents us from exploring what the impact of different PHSM settings could be.

Commented [PP36]: Would be good to use something

Commented [PP37]: Ceiling or proportional reduction?

Commented [PP38]: Need to provide a number that reflects actual capacity – not of all beds, but of beds that can be spared from BAU for COVID..?

Commented [PP39]: Test sensitivity could be reviewed.

Commented [PP40]: Sensitivity analysis 10%, 30%, 40%? We think we've hit over 40% in several areas in this outbreak, so it is feasible..

- Effectiveness of pre-symptomatic quarantine = 50%
- For now: contact tracing parameters assumed to be constant regardless of number of active cases
- Hospitalisation, ICU and death rates by age for Delta
- Mean length of hospital stay = 8 days

From: Christopher Nees [TSY]
To: Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; [redacted]; Ian Town; pmcsa; ^EXT: Talosaga Talosaga; [redacted]
Cc: George Whitworth [DPMC]; [redacted]; Gill Hall; [redacted]; Patricia Priest; [redacted]; Caleb Morrall [TSY]; Harry Nicholls [TSY]
Subject: RE: Covid-19 Modelling Governance Group
Date: Tuesday, 31 August 2021 2:01:00 PM
Attachments: image001.png

Kia ora koutou

Our proposed agenda for this Friday is:

1. An overview of the modelling on the current resurgence. This is to give you a picture of the latest work and understand our modelling cycle with TPM.
2. Latest draft results on the 'border reopening scenarios' paper. We introduced this work at the last meeting and have an updated but not final draft from TPM
3. Proposed modelling work on options for managing COVID-19 as vaccination rates increase. This work is similar to what has been recently undertaken in Australia and aims to look at what bundles of public health restrictions are sufficient to control resurgences when vaccination rates are high, how long they are needed for, and their economic impacts.

Please let me know if you have further items you'd like to cover.

Ngā mihi

Chris Nees| Principal Advisor | Economic Strategy Directorate |Te Tai Ōhanga – The Treasury
Mobile: +s9(2)(g)(ii) [redacted]
Visit us online at https://treasury.govt.nz/ and follow us on Twitter, LinkedIn and Instagram

I do not work on Thursdays.

-----Original Appointment-----
From: Steph Tims [TSY] <[redacted] **On Behalf Of** Bryan Chapple [TSY]
Sent: Wednesday, 18 August 2021 5:05 PM
To: Bryan Chapple [TSY]; Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; [redacted]Ian Town; pmcsa; ^EXT: Talosaga Talosaga; [redacted]Christopher Nees [TSY]; Harry Nicholls [TSY]; Caleb Morrall [TSY]
Cc: George Whitworth [DPMC]; [redacted]Gill Hall; [redacted]Patricia Priest; [redacted]
Subject: Covid-19 Modelling Governance Group

When: Friday, 3 September 2021 12:45 PM-1:30 PM (UTC+12:00) Auckland, Wellington.
Where: (MS Teams); +TSY 3.30 Purapura -46 -MS Teams (EXT)

Hi all –
Rescheduling this from 20/8 to 3/9 – apologies for hijacking the lunch break!
Agenda and papers will be circulated in advance.

Cheers. Steph

Steph Tims (she/her) | **Te Tai Ôhanga – The Treasury**
Executive Assistant to Bryan Chapple, Deputy Secretary – Macroeconomics & Growth
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From:	Christopher Nees [TSY]
To:	Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; [redacted]; Ian Town; pmcsa; Juliet Gerrard [DPMC]
Cc:	Ivan Luketina [DPMC]; Patricia Priest; Patricia Priest; ^EXT: Talosaga Talosaga; Gill Hall; Hamish Spencer; Kerryn Fowlie; Alastair Cameron [TSY]; Harry Nicholls [TSY]; George Whitworth [DPMC]; Pubudu Senanayake
Subject:	FW: In Confidence, Under Embargo COVID-19 vaccine strategies for Aotearoa New Zealand: a mathematical modelling study Lancet Publication
Date:	Wednesday, 11 August 2021 5:22:00 PM
Attachments:	HRC COVID-19 Vaccination Modelling 5.1 .pdf HRC COVID-19 VM Supplementary material 5.1 .pdf image003.png

Kia ora koutou Modelling Governance Group

This is to let you know about the upcoming release of the attached ESR report on COVID-19 vaccine strategies for Aotearoa New Zealand. The report is embargoed until it is published in the Lancet likely on Friday. With thanks to Ivan, here's some context and key messages from the report – overall the results are consistent with the report that TPM released last month on the vaccine roll out.

Context

- The Institute of Environmental Science and Research (ESR) have shared with us an embargoed copy of a modelling report that estimates the impacts of COVID-19 outbreaks under different domestic vaccination scenarios, in order to inform an optimum approach.
- The report has been submitted to the Lancet Regional Health – Western Pacific, and will be published this week, likely on the Friday 13 August. The Steering Group has seen a previous iteration of the report, but it has since been updated to reflect the potential for outbreaks of the delta variant.
- The modelling will help us to understand the different impacts that could occur if re-opening occurred under different domestic vaccination scenarios. It is important to note that the study simulates open borders, with unvaccinated travellers, in order to see the impact of unmitigated spread. This is not a realistic real world scenario.

Results

- The report evaluates two approaches; optimising the vaccine rollout to reduce spread and, optimising the vaccine rollout to reduce the impacts of disease by targeting high risk populations. The high risk population approach was found to reduce the impact of hospitalisation and deaths compared with a spread minimising approach.
- Consistent with modelling from Te Pūnaha Matatini (TPM) the report showed continued gains from vaccination in terms of reducing health impacts. With the assumptions of open borders and unmitigated spread in all scenarios even with very high vaccination coverage there were hospitalisations and deaths. Although this is an unrealistic policy approach.
- The model also tested the herd immunity threshold, the point at which most outbreaks would self-eliminate. Their findings were again consistent with modelling undertaken by TPM, in that very high rates of domestic vaccination would likely be needed (98% +) in the case of outbreaks with an R_0 of 6 (delta variant).

Ngā mihi

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I do not work on Thursdays.

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From: Brett Cowan <xxxxx.xxxxx@xxx.xxx.xx>
Sent: Tuesday, 10 August 2021 2:47 PM
To: Christopher Nees [TSY] <xxxxx.xxxx@xxxxxxxx.xxxx.xx>
Subject: In Confidence, Under Embargo COVID-19 vaccine strategies for Aotearoa New Zealand: a mathematical modelling study Lancet Publication

Kia ora Christopher,

[In Confidence], Under Embargo

We are pleased to confirm The Lancet Regional Health - Western Pacific are scheduled to publish the paper 'COVID-19 vaccine strategies for Aotearoa New Zealand: a mathematical modelling study'. The date for the release of this has yet to be confirmed but is likely to be later this week. ESR anticipates announcing the finding of this study on Friday, 13 August.

The study was led by Prof. Colin Simpson (Wellington Faculty of Health) in a collaboration with ESR and other NZ experts across national infectious disease, epidemiology, public health, statistics and computer science.

As you may recall, the aim of the study was intended to provide age-related optimisation and simulation results that can be used to design optimal vaccine programmes; including (1) achievement of herd immunity and, (2) if borders are open and cases of COVID-19 are introduced to the NZ community, minimisation of COVID-19 cases, hospitalisations and deaths.

The previous draft of the study you may have received did not reflect the delta variant, and following a peer review the final study now includes results for higher Ro values to account for this. As a result, the likely impact of the changes to our border status is significantly greater than in the original draft.

The key findings of the study are:

- A safe and staged relaxation of borders requires a very high vaccine uptake to

provide the best chance of minimising the anticipated increase in COVID-19 positive cases, hospitalisations and deaths that would occur over a two-year period;

- A strategy targeting high-risk groups will result in lower hospitalisations and deaths, but a higher number of cases compared to a strategy targeting reduced transmission;
- Reaching the herd immunity threshold (HIT) with a vaccine of 90% vaccine effectiveness (VE) against disease and 80% VE against infection requires at least 86·5% total population uptake for Ro=4·5 (with high vaccination coverage for 30–49-year-olds) and 98·1% for Ro=6;
- In a two-year open-border scenario with 10 overseas cases daily and 90% total population vaccine uptake (including 0–15 year olds), the modelling estimates 11,400 total hospitalisations (peak 324 active and 36 new daily cases in hospitals), and 1,030 total deaths; and
- That other public health and social measures will still be required as part of an effective pandemic response.

ESR has created an interactive dashboard to help predict outcomes based against a range of inputs and factors which we would be happy to share with you. This will also be publicly available.

We recognise the strategy to reopen borders to vaccinated travellers is being actively considered by Government and we would welcome the opportunity to discuss this modelling and the communications of the findings with you and your colleagues.

Best regards

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COVID-19 vaccine strategies for Aotearoa New Zealand: a mathematical modelling study

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Summary

Background: COVID-19 elimination measures, including border closures have been applied in New Zealand. We have modelled the potential effect of vaccination programmes for opening borders.

Methods: We used a deterministic age-stratified Susceptible, Exposed, Infectious, Recovered (SEIR) model. We minimised spread by varying the age-stratified vaccine allocation to find the minimum herd immunity requirements (the effective reproduction number $R_{eff}<1$ with closed borders) under various vaccine effectiveness (VE) scenarios and R_0 values. We ran two-year open-border simulations for two vaccine strategies: minimising R_{eff} and targeting high-risk groups.

Findings: Targeting of high-risk groups will result in lower hospitalisations and deaths in most scenarios. Reaching the herd immunity threshold (HIT) with a vaccine of 90% VE against disease and 80% VE against infection requires at least 86·5% total population uptake for $R_0=4·5$ (with high vaccination coverage for 30–49-year-olds) and 98·1% uptake for $R_0=6$. In a two-year open-border scenario with 10 overseas cases daily and 90% total population vaccine uptake (including 0–15 year olds) with the same vaccine, the strategy of targeting high-risk groups is close to achieving HIT, with an estimated 11,400 total hospitalisations (peak 324 active and 36 new daily cases in hospitals), and 1,030 total deaths.

Interpretation: Targeting high-risk groups for vaccination will result in fewer hospitalisations and deaths with open borders compared to targeting reduced transmission. With a highly effective vaccine and a high total uptake, opening borders will result in increasing cases, hospitalisations, and deaths. Other public health and social measures will still be required as part of an effective pandemic response.

Funding: This project was funded by the Health Research Council [20/1018].

Research in context

Evidence before this study

We searched PubMed, medRxiv and SSRN for modelling studies using the term "COVID-19 vaccine AND model AND New Zealand". We found one study by Bubar et al. which investigated age-related vaccine allocations to minimise the total deaths for countries without community transmission where total vaccination supply was limited to 50% of the population and found that direct vaccination of adults aged over 60 years nearly always reduced mortality. Moore et al. predicted a reproduction number of 1·58 after implementing vaccination in the UK and highlighted the risks of early relaxation of non-pharmaceutical interventions. Sandmann et al. also considered, in a 10-year simulation, the economic impact in the UK and suggested that with COVID-19 vaccination, small outbreaks could continue.

Added value of this study

To our knowledge, this is the first detailed COVID-19 vaccination programme modelling for Aotearoa New Zealand, a country with closed borders and a COVID-19 elimination strategy. We forecast the effect of strategies of minimising disease spread in the community and prioritisation of high-risk age groups. We modelled different vaccination programme strategies for the following health outcomes: number of cases, hospitalisations, and deaths over two years with open borders.

Implications of all the available evidence

To achieve the herd immunity threshold (HIT) (where R_0=4·5), and limit community transmission (e.g. sporadic outbreaks) once borders are opened, a vaccine that has a vaccine effectiveness of 90% for disease prevention and 80% for infection reduction will require high vaccination coverage for 30–49-year-olds, and at least 86·5% total population uptake. A number of possible scenarios were modelled including where 10 overseas cases are introduced

daily with open-borders and 90% total population vaccine uptake with a vaccine with VE of 90% for disease prevention and 80% for infection reduction, and prioritisation of high-risk groups for vaccination. In the two-year simulation, this scenario was forecasted to have 11,400 total hospitalisations (peak 324 active and 36 new daily cases in hospitals), and 1,030 total deaths. Where 0–12 year olds are not vaccinated and total population uptake is 80% (the maximum uptake is 84·9% and HIT is not achieved) there is an estimated 37,700 total hospitalisations (peak 2,980 active and 343 new daily cases in hospitals), and 3,120 total deaths. Other non-pharmaceutical interventions will still be required to sustain the pandemic response. These findings can support policy makers in New Zealand (including the Ministry of Health) to inform their vaccination programme and is generalisable to other countries with closed borders and elimination strategies to ensure optimal vaccination programmes.

Introduction

COVID-19 has caused widespread morbidity and more than 4·0 million deaths globally as of July 9th, 2021[1] with extensive social and economic consequences.[2] To prevent COVID-19 outbreaks, New Zealand (NZ) adopted an early elimination strategy with non-pharmaceutical interventions, referred to as public health and social measures (PHSMs) in this paper.[3,4]

PHSMs, such as border controls, lockdown measures, quarantine, and comprehensive testing, surveillance, and contact tracing, have led to the elimination of COVID-19 transmission in NZ, but there are expectations that NZ will begin to reopen its border once the vaccination programme has progressed. Opening borders without strict isolation will continuously introduce COVID-19 to the community. The NZ government is undertaking a vaccination programme[5] to protect NZ communities. Vaccination modelling can help anticipate potential public health outcomes based on different vaccine effectiveness (VE) reported in clinical trials[6] and 'real-world' studies,[7-10] and vaccination programme strategies.[5] Estimates of the minimal vaccine coverage for herd-immunity with vaccines of different effectiveness, for instance, is needed. Vaccine allocation strategies should also take into account the potential ranges of VE in disease prevention (70–95%) and infection reduction (30–90%) from the first available vaccines including BNT162b2, mRNA-1273, and ChAdOx1 (AZD1222) vaccines.[6-13]

The aim of this study was therefore to provide age-related optimisation and simulation results that can be used to design optimal vaccine programmes; including: i. achievement of HIT and, ii. if borders are open and cases of COVID-19 are introduced to the NZ community, minimisation of COVID-19 cases, hospitalisations and deaths. These include strategies to ensure maximum protection for Māori and Pasifika populations, who are at higher risk for hospitalisation and death from COVID-19.[14,15]

Methods

We extended an age-stratified Susceptible, Exposed, Infectious, Recovered (SEIR) model[16] with a presymptomatic phase to include vaccinated compartments (Supplemental Figure S1). The whole population is divided into eight 10-year age groups G={0–9,10–19,20–29…,60–69,70+}.

We assume that a vaccine has three effects: e_i is the reduction of infection in vaccinated people (i.e. susceptibility to infection), e_d is the VE for disease prevention (the default concept of VE and commonly used clinical endpoint in vaccine efficacy trials), and the third effect is reduction of infectiousness. The vaccine effect on infection reduces the susceptibility of vaccinated people by a factor e_i compared with unvaccinated people. Thus, if the susceptibility of an unimmunised person in an age group i is u_i, the susceptibility of a vaccinated person in the same age group is expected to be $u_i^v = u_i(1 - e_i)$. e_i has a direct influence on the viral transmission. Likewise, the probability of developing clinical disease in vaccinated infected cases in age group i is $\rho_i^v = \rho_i(1 - e_d)/(1 - e_i)$, where ρ_i is the probability of having clinical disease in unvaccinated infected cases. e_d is, thus, the effect of the vaccine on preventing disease in vaccinated individuals and corresponds to the reported vaccine efficacy and effectiveness.[6-13] The effect of the vaccine on the reduction of infectiousness reduces the probability of spreading SARS-CoV-2 in vaccinated individuals. A detailed description of the model can be found in the Supplementary Appendix S1.

In addition to e_i, another effect of vaccines that contributes to the change of the effective reproduction number R_{eff} is the reduction of infectiousness in vaccinated infections.[17] This parameter is dependent on the reduction of viral shedding and/or symptoms (e.g., coughing and sneezing). In our model, it is considered that the reduction of infectiousness is a result of the reduction of clinically disease in vaccinated infections and the parameter f (Supplemental Table

S1). This dependency is different from considering a constant reduction of infectiousness across all age groups, where different rates of symptom reduction does not influence the reduction of infectiousness in vaccinated infections. This model enables us to model the effect of e_d on the overall transmission (R_{eff}) while analysing the vaccine effect on reducing infection (e_i).

Model assumptions

Model assumptions included: i. For open-border modelling the behaviour of New Zealanders is as observed prior to Alert level 1 (without PHSMs). The average duration from illness onset to isolation without any intervention is 7·2 days;[3] ii. age group sizes are constant in the open-border modelling; iii. infected, vaccinated people, without disease, have the same spreading capability as the infected asymptomatic/paucisymptomatic cases without vaccination; iv. the effectively immunised people, against either infection or disease, stay immunised with the same protection effect for the whole simulation period if they do not get re-infected. This can be interpreted as the waning vaccination effect (in the vaccinated group) being balanced by the reinforcement of the vaccination process during the simulation period. This assumption is to separate other effects from the vaccine distribution; v. vaccines are as effective for children and teenagers (age below 16) as they are for other tested age groups; vi. Māori and Pasifika populations have the same contact matrix as the whole of NZ.[18] This assumption is, however, likely to underestimate the actual contact frequencies in this population[19] as Māori and Pasifika people live in larger households, have larger social networks (inter-dependent households, family, church etc), have a higher proportion of the population that are young, as well as a greater likelihood of being in high exposure risk occupations;[20] and vii. death rates (total rate and age-specific rates) are unchanged even when the active COVID-19 hospitalisations exceeds available NZ hospital capacity.[21]

Data

We used COVID-19 case data reported in EpiSurv[22] from February 26th 2020 (when the first case was reported) to October 21st, 2020. COVID-19 hospitalisation rates for all age groups were inferred from recorded hospitalised cases in the national notifiable disease surveillance system, EpiSurv.[22] We assumed that Māori and Pasifika populations have twice the hospitalisation rates estimated from EpiSurv based on previous evidence.[15] We used the estimated age-stratified infection fatality rates modelled by Verity et al.[23] as the age-stratified death rates for the whole of NZ, and the rates modelled by Steyn et al.[14] as the age-stratified death rates for Māori and Pasifika populations. We used the age distribution of imported cases as recorded in EpiSurv[22] as the age distribution of imported cases in the model (70.6% were aged 20-59 years). The susceptibility and clinical rates of COVID-19 for different ages were calculated using data from an age-stratified model published by Davies et al.[16] A list of parameters with their source is shown in Supplemental Table S1.

Strategies and scenarios

Vaccine effectiveness

We investigated vaccine scenarios that only one vaccine is used for the whole population regarding NZ vaccine plan.[5] We analysed varying effects of the vaccine by introducing a parameter for the effectiveness on disease prevention, e_d, and a parameter for the effectiveness on infection reduction, e_i. We looked at minimum vaccine effectiveness with different uptake levels (from 60% to 100% coverage of total population) required to achieve HIT ($R_{eff}<1$) given the R_0 values of 2·5, 4·5, and 6.

We modelled VE (of disease prevention) in the range of 70–95%. VE of infection reduction is normally smaller than VE of disease prevention. Thus, the range of VE for infection reduction was 30% to 90% and was no greater than VE of disease prevention in all scenarios. Hereinafter, the effects of a vaccine with VE of disease prevention (e_d) and VE of infection reduction (e_i) is

shortened to e_d/e_i% effectiveness for convenience. For instance, a vaccine with 95/70% effectiveness has 95% effectiveness for disease prevention and 70% effectiveness for infection reduction. The effectiveness of a vaccine is considered "uniform" when their effectiveness is equal across age groups, while the effectiveness is called "varied" when the vaccine effectiveness is reduced in older age groups. The current vaccination strategy in NZ focuses on two dose vaccination, rather than maximising the number of administrations of first dose. The second dose is administered at least 21 days after the first dose.[5]

Vaccine strategies with closed borders

In this study, we compared two vaccine strategies, where each could be implemented through one of the following optimisation criteria: (1) minimising the effective reproduction number or the spreading rate; and (2) minimising disease in the total high-risk population (risk for severe disease and deaths). The first strategy minimises the leading eigenvalue of the next generation matrix (i.e. R_{eff}) or the spreading rate. This strategy requires minimum requirements for vaccine effectiveness and the total uptake to achieve HIT. Therefore, it is used to analyse the minimum herd immunity requirements. The total high-risk population in the second strategy can be estimated as $\sum_i S_i d_i$, which are the age-stratified susceptible populations (S_i) weighted by their mortality rates due to COVID-19 (d_i). This strategy begins with vaccination in the oldest groups, followed by the younger groups, because older groups are known to have higher risks for both severe disease and death.[24,25] Hereafter, two strategies are referred to as the spread-minimising/minimise R_{eff} strategy and the high-risk (group) targeting strategy respectively. A third strategy that balances between these two strategies is included in Supplemental Appendix S2.

Both strategies are assumed to be implemented with closed borders until a certain uptake level is reached, i.e. from 60 to 100% total population coverage (Figure 1). A vaccination uptake of 80–90% of the NZ population requires vaccinating individuals aged under 16 and a higher rate

of vaccination than being achieved in other countries. In the United Kingdom, Israel, and Canada,[26] around 60% of total populations have been vaccinated with more than 95% in older age groups.

We assumed the following constraints on all vaccine strategies: i. each age group is vaccinated at least 20%, except for the 70+ year olds with minimum 80% vaccine coverage. ii. the maximum coverage for each age group is 90% for variants with lower R_0 values (2–3·5) and 100% for variants with higher R_0 values (4·5–6). The range of the higher R_0 values corresponds to the early estimates of R_0 values for the variants of concern (4·5–6).

To compare these strategies, we ran two-year simulations of two vaccine strategies with open borders, where a continuous vaccination process is assumed to mitigate any potential waning effect of the vaccine (Figure 1). We assumed there is a constant ten daily imported cases that become part of the community, which are equivalent to a total of 7,300 imported cases. As part of a sensitivity analysis, we also modelled on 100 daily imported cases (73,000 total). Imported cases are assumed to be unvaccinated. Comparison criteria include total COVID-19 deaths, total community cases, peak active cases, total hospitalisations, and peak active hospitalised cases (peak hospitalisations). The measures relating to hospitalisations and deaths include a predicted 444 total hospitalised and 84 deaths from 7,300 imported cases (Supplemental Appendix S2). As vaccination has not been approved for 0–15 year olds in New Zealand,[5] we carried out a sensitivity analysis where uptake was 0% for 0–9 year olds and the vaccine coverage of 10–19 year olds is assumed to have a maximum level of 35% as the subgroup of 16–19 year olds contribute nearly 40% to the group of 10–19 year olds.[27] We also limited our analysis to 0–11 year olds (as clinical trials have yet to release findings). For this analysis, the vaccine coverage of 10–19 year olds is therefore assumed to have a maximum level of 70% as the subgroup of 12–19 year olds contribute about 79% to the group of 10–19 year olds.

Ethics and permissions

The study protocol was approved by the Health and Disability Ethics Committee, New Zealand, under the protocol number 20/NTB/156.

Role of the funding source

The sponsors of the study had no role in study design, data collection, data analysis, data interpretation, or the writing of this report.

Results

Minimum herd immunity requirements

Figure 2 (A-B) and Figure 4 (A-D) show minimum herd immunity requirements for two vaccine strategies at multiple uptake levels given the R_0 value is in the range of 4·5–6 and 2–3·5 where there is a minimum 80% vaccine uptake for high risk groups. Reaching the HIT with a vaccine of 90/80% effectiveness requires at least 86·5% total population uptake for R_0=4·5 and 98·1% uptake for R_0=6 with high vaccination coverage for 30–49-year-olds, i.e. the spread-minimising strategy. With the same vaccine and the high-risk targeting strategy, reaching HIT requires 92% and 99·2% total population uptake levels for R_0=4·5 and 6 respectively. With 90% total population coverage with a vaccine of 90% VE for disease prevention, a minimum 76% VE of infection reduction for R_0=4·5 and 86% VE of infection reduction for R_0=6 is required (using the spread-minimising strategy). For 80% population vaccine coverage, a VE of 87% for infection reduction is needed. For all VE scenarios (Figures 2, 4, Supplemental Appendix S3), the spread-minimising strategy has the minimum requirements of VE for HIT among vaccine strategies given the same uptake levels although it may not be optimal for protecting the whole population from the risk of hospitalisations and deaths. Vaccinating the age groups 30–39 and 40–49 can minimise the initial effective reproduction numbers (given a limited number of doses), while 60+ and 0–9 are the age groups that contribute the least to the reduction of the effective reproduction number and the achievement of HIT.

Open border modelling results

The differences in vaccine allocation of the investigated strategies can be found in Figure 3. The spread-minimising strategy (minimise R_{eff}) in this figure has enabled HIT at 80% total population coverage. Probable scenarios of VE and vaccine uptake levels in a two-year simulation of the model can be found in Table 1 (open borders, ten cases daily introduced to the community and R_0=4·5). Further vaccine scenarios for the whole NZ can be found in Supplemental Tables S2–8.

The spread-minimising strategy (i.e. minimise R_{eff}) resulted in the smallest peak and total community cases in all scenarios (assuming the vaccine can reduce infection $e_t > 0$). The strategy which targeted high-risk groups yielded the fewest hospitalisations (active or total) and total deaths in the majority of modelled scenarios (Table 1). For the high-risk group targeting strategy, a high total vaccine uptake is required that is enough to also cover young adults to achieve better outcomes in general. For instance, in a scenario with R_0=4·5 and a vaccine having a VE of 90/70% and 90% population uptake, the high-risk group targeting strategy was forecasted to have the lowest number of deaths and total hospitalisations, i.e. 2,880 vs 5,810 fatalities and 30,100 vs 39,700 hospitalisations (peak active hospitalisations 1,480 vs. 1,310) respectively, and more community cases than the spread-minimising strategy, i.e. a total of 1,490,000 vs. 1,200,000 cases (peak active community cases 63,100 vs. 34,000). Where the R_0 value is 6 and 90% total population uptake with the same vaccine, modelling the high-risk group targeting strategy resulted in lower hospitalisations and deaths but higher cases than the spread-minimising strategy, i.e. 6,100 vs. 11,700 deaths, 59,600 vs. 82,600 hospitalisations (peak active 5,960 vs. 7,320), 2,860,000 vs. 2,750,000 cases (peak active community cases 253,000 vs. 213,000).

A dual vaccine approach has been investigated where the vaccine distribution follows the high-risk targeting strategy (Table 1). All groups aged 50 and over are allocated with a vaccine of

90/80% effectiveness and the rest are allocated with a vaccine of lower 70/50% effectiveness. The outcomes of this scenario are 2,180,000 cases (peak active 175,000 cases), 95,300 hospitalisations (peak active 8,410 in hospital), and total 12,000 fatalities. These numbers are in between the corresponding outcomes of two scenarios using either one of the two vaccines.

We have modelled vaccine scenarios of immunesenescence with a 50% reduction in effectiveness (for both disease prevention and infection reduction) in people aged 60 and over (Supplemental Table S9). We also analysed the sensitivity of the results on the assumed average daily imported cases and the synthetic contact matrix[18] in Supplemental Appendix S4. Customised vaccine strategies and open-border modelling results for Māori and Pasifika populations are provided in Supplemental Appendix S5.

Vaccination excluding youngest age-groups

Where vaccination is not allocated to the 0–15 year olds[5] or the 0–11 year olds, the maximum attainable total population vaccine coverage is 79·8% or 84·9%. At a high R_0 value of 4·5 or higher, these maximum total coverage levels are not enough to achieve HIT. Therefore, opening borders without vaccinating the under-12 group or the under-16 group were predicted to result in a large number of cases, hospitalisations, and deaths (Table 2 and Supplemental Table S2). For instance, where 0–11 year olds are not vaccinated and R_0=4·5 (Table 2), the high-risk targeting strategy with a high uptake level 80% (over the maximum 84·9%) and a vaccine of 90/80% effectiveness was predicted to have lower deaths and total hospitalisations and more community cases, i.e. 3,120 vs. 5,850 deaths, 37,700 vs. 44,100 hospitalisations (peak 2,980 vs 2,630), 1,480,000 vs 1,180,000 cases (peak 107,000 vs 62,700).

At a lower R_0 value of 2·5 (Figure 4 and Supplemental Figures S5-6), the achievement of HIT will require a minimum VE against infection of 61% for excluding 0–15 year olds and 73% for excluding 0–11 year olds with the limits of 76·4% and 71·8% respectively (maximum 90%

coverage for each age group). The open border modelling outcomes have higher numbers of cases, hospitalisations, and deaths in almost all scenarios and vaccine strategies compared with vaccinating all age groups.

Discussion

Reaching HIT will prevent widespread community outbreaks and, as a result, vulnerable populations will have a greater chance of protection from severe disease. A long-term lockdown may only postpone future outbreaks if a high level of immunity (by vaccination or natural immunity) is not targeted. Achieving HIT through vaccination in New Zealand while borders are closed will require an effective vaccine that can reduce infection and high national vaccine uptake. Achievement of HIT without vaccinating the youngest age groups will require a vaccine with higher VE against infection. In an open border scenario with the relaxation of PHSMs and a highly effective vaccine for both disease prevention and infection reduction, targeting high-risk groups (including Māori and Pasifika) and achieving a high national uptake level, e.g. 80%, will result in a relatively low number of forecasted COVID-19 hospitalisations and deaths by international comparisons.[28] Where the vaccine has lower VE for infection reduction, more COVID-19 cases, hospitalisations and deaths are likely.

A strategy to achieve HIT will ensure limited community transmission (e.g. sporadic outbreaks) once borders are opened but would require a vaccine with a minimum 87% VE for infection reduction (where R_0=4·5) and a high vaccine coverage rate of 80% total population. This estimated VE for infection reduction is higher than the 85% effectiveness for preventing infections that was predicted to result in a reproduction number of 1·58 in the UK. This study did not however account for further reduced viral shedding from vaccinated individuals, reducing onward transmission.[28]

Although, HIT is potentially possible e.g. with recent evidence of the BNT162b2 vaccine' effect against infection,[29] it is also possible that emerging effectiveness challenges against new virus variants will necessitate a shift in focus away from herd immunity strategies to protection of at-risk individuals against severe disease.[30] Although the range of estimated VE used in this study are plausible, in particular for the mRNA vaccines licensed in NZ,[11] the lower bounds of VE may need to be extended in the presence of variants of concern.[31]

Comparisons of our forecast peaks (with 80% uptake, and 95% VE for disease and 70% for infection) with other countries who had widespread community transmission during the first waves of disease (with no available vaccination) can be made. Scotland has a broadly comparable population size but higher population density (e.g. Scotland, UK, 5·4m vs. 5·1m population, 19·0/km^2 vs. 67·2/km^2). Variants of concern with high R_0 values such as Alpha [32] and Delta variants,[33] were dominant in Scotland in Spring 2021. In an open border scenario, our NZ model for R_0=4·5, where a vaccine of 90/80% effectiveness is not allowed for individuals aged under 16, has estimated a peak of 355 new daily hospitalisations (3,090 peak active hospitalised cases) vs. 92 peak daily hospitalisations found during the ongoing wave in Scotland (from June until July 2021), and higher peak daily cases 14,800 (including asymptomatic cases, 110,000 peak active cases) vs. 3,930 found in Scotland with 64·7% two-dose vaccine coverage and 88·1% first-dose vaccine coverage of all people aged 18 and over.[34] The numbers hospitalisations and deaths for NZ will be higher as this includes 7,300 unvaccinated imported cases.

Several studies have addressed COVID-19 vaccination strategies. Bubar et al.[35] compared five vaccine strategies that allocate vaccine doses on 'under 20', 'adults 20–49', 'adults 20+', 'adults 60+', and 'all ages' in terms of the reduction of deaths and infections. This study focused on the initial phase of vaccination, modelling a total vaccine uptake of no more than 50% of the population and applying non-pharmaceutical interventions to reduce the spreading

rate. Moore et al. predicted 96,700 deaths (51,800–173,200) if interventions are removed after vaccination with a vaccine that could prevent 85% infections.[28] Sandmann et al. used an age-structured transmission and economic model to estimate the economic impact of vaccination for the UK in a ten-year simulation.[36] This study suggested that vaccination could add substantial health and economic value and population-wide physical distancing might not be justifiable.

Compared with other models used for vaccination studies, the SEIR model used in this study provides a model with fewer assumptions for the same disease dynamics. By grouping individuals of the same disease phase into a compartment, this SEIR model approach only requires transitions among phases instead of requiring numerous rules representing all the disease phases that are used in agent-based models. Although agent-based models have been used to apply a number of assumptions which are useful for understanding the effect of multiple public health interventions, they have limitations due to being computationally demanding.[37] For instance, agent-based models do not integrate age groups, but use averages for the whole population, whereas we know that vaccine distribution across age groups is unlikely to be uniform.[38] The required uptake levels for HIT are subject to an estimated basic reproduction number R_0 of COVID-19 in NZ, national priorities and consideration to protect health and social care workers and the most clinically susceptible groups. While the R_0 value for NZ has not been reliably estimated, its actual value is also probably dependent on seasonality.[39,40] Moreover, R_0 is likely to increase with the emergence of the new virus strains.[41,42] To consider possible increases in R_0, a strength of this study is that we also investigated herd immunity requirements for higher R_0 values (4·5 and 6). These R_0 values could be the potential reproduction number of new variants. However, this study does not include changing R_0 values over time (with the introduction of new variants of concern). Rather R_0 values are fixed for the two-year period. Another strength of this work is that the model can be calibrated when more

accurate parameter values are available. There is uncertainty with new variants of concern. Model parameters, such as R_0, latent/infectious periods, and age-structured mortality rates may therefore vary. However, further parameters can be added to the model once evidence of new parameters emerges.

The safe opening of borders in NZ will be dependent on a vaccine that has high effectiveness against both COVID-19 disease and viral transmission. A limitation of our study is that there is still some uncertainty regarding the vaccine effectiveness against transmission. Therefore, modelling strategies and scenarios and forecasting their potential impact on the NZ population with more accurate assumptions (including infection reduction and waning vaccine immunity) needs further investigation. A further limitation is uncertainty around the potential number of imported cases in particular if travel is restricted from regions with high numbers of cases. There is also uncertainty regarding immunesenescence and our assumption of uniform effectiveness across age groups may not hold, although we have modelled vaccine scenarios with a reduction in effectiveness (for both disease prevention and infection reduction) in people aged 60 and over. The targeting of high-risk groups (in an open border scenario), in this case, may not yield the lower total deaths in many scenarios as the disease prevention effect is now lower. This is in contrast to another modelling study which found that, in the event of low effectiveness amongst older adults and no more than 50% uptake level, the advantage of prioritising all adults or adults 20–49 vs. adults 60+ was small.[35]

This work provides data on a range of vaccine scenarios and strategies to inform NZ vaccine planning.[5] While research to estimate vaccine effectiveness for reducing severe outcomes and infection is underway, a 70% VE against infection is predicted to be the minimum required to achieve HIT for NZ with an R_0=4·5 and 95% total vaccine coverage. As NZ's vaccination plan has not yet included those aged 0–15 years for vaccination,[5] achievement of HIT without vaccinating this group may be impossible, especially if the imported cases are Alpha or Delta

variants of concern.[33] Thus, to help reduce cases, hospitalisations, and deaths, other public health interventions will be required to manage the public health response.

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Table 1: **Comparison of cases, hospitalisations, and deaths in New Zealand population (R_0=4·5) – 10 imported cases per day with open borders or 7,300 total imported cases with two-year open borders**

Vaccine scenarios (e_d/e_i & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 100% coverage	n/a	133	5,010	7	587	64
95/90% uniform 90% coverage	minimise R_{eff}	**217**	**12,100**	15	1,170	173
	high-risk	1,380	80,400	34	1,950	145
	hybrid	270	16,800	**10**	**814**	**77**
95/90% uniform 80% coverage	minimise R_{eff}	**1,090**	**75,700**	**78**	**5,210**	**863**
	high-risk	66,700	821,000	1,530	17,400	947
	hybrid	1,950	127,000	123	7,490	1,150
95/90% uniform 70% coverage	minimise R_{eff}	**46,500**	**974,000**	**2,910**	55,200	8,140
	high-risk	163,000	1,500,000	3,640	**31,700**	**1,710**
95/80% uniform – 100% coverage	n/a	272	18,100	9	708	76
95/80% uniform 90% coverage	minimise R_{eff}	**584**	**43,500**	29	2,120	333
	high-risk	7,050	318,000	127	5,130	383
	hybrid	803	60,100	**28**	**2,010**	**261**
95/80% uniform 80% coverage	minimise R_{eff}	**16,600**	**673,000**	**908**	**32,200**	**5,440**
	high-risk	110,000	1,360,000	2,050	22,800	1,400
95/80% uniform 70% coverage	minimise R_{eff}	**122,000**	**1,790,000**	5,840	75,400	11,100
	high-risk	240,000	2,140,000	**4,480**	**36,900**	**2,190**
95/70% uniform – 100% coverage	n/a	1,560	119,000	24	1,630	168
95/70% uniform 90% coverage	minimise R_{eff}	**14,600**	**734,000**	**459**	19,600	3,210
	high-risk	42,600	1,180,000	575	**13,700**	**1,130**
95/70% uniform 80% coverage	minimise R_{eff}	**91,900**	**1,820,000**	3,560	60,100	9,910
	high-risk	188,000	2,200,000	**2,800**	**28,900**	**1,960**
95/70% uniform	minimise R_{eff}	**236,000**	**2,650,000**	8,970	87,900	12,900

70% coverage	high-risk	341,000	2,830,000	**5,330**	**40,400**	**2,530**
95/60% uniform – 100% coverage	n/a	59,500	1,590,000	561	12,700	1,330
95/60% uniform	minimise R_{eff}	**119,000**	**2,190,000**	2,500	39,300	6,260
90% coverage	high-risk	146,000	2,340,000	**1,540**	**21,200**	**1,870**
95/60% uniform	minimise R_{eff}	**221,000**	**2,800,000**	6,670	72,400	11,900
80% coverage	high-risk	303,000	2,990,000	**3,670**	**32,300**	**2,300**
95/60% uniform	minimise R_{eff}	**370,000**	**3,330,000**	11,700	92,600	13,700
70% coverage	high-risk	455,000	3,390,000	**6,060**	**41,600**	**2,670**
90/80% uniform – 100% coverage	n/a	337	23,200	15	1,140	120
90/80% uniform	minimise R_{eff}	**918**	**67,500**	**54**	**3,750**	**559**
90% coverage	high-risk	11,100	439,000	324	11,400	1,030
	hybrid	1,470	105,000	71	4,640	609
90/80% uniform	minimise R_{eff}	**29,200**	**928,000**	**1,780**	50,100	7,890
80% coverage	high-risk	122,000	1,500,000	3,430	**38,800**	**3,170**
90/80% uniform	minimise R_{eff}	**145,000**	**1,960,000**	7,770	94,400	13,200
70% coverage	high-risk	259,000	2,260,000	**7,020**	**58,600**	**4,590**
90/70% uniform – 100% coverage	n/a	5,170	329,000	130	7,060	720
90/70% uniform	minimise R_{eff}	**34,000**	**1,200,000**	**1,310**	39,700	5,810
90% coverage	high-risk	63,100	1,490,000	1,480	**30,100**	**2,880**
90/70% uniform	minimise R_{eff}	**121,000**	**2,080,000**	5,400	80,600	12,200
80% coverage	high-risk	212,000	2,390,000	**4,910**	**49,900**	**4,320**
90/70% uniform	minimise R_{eff}	**267,000**	**2,810,000**	11,400	107,000	15,000
70% coverage	high-risk	366,000	2,950,000	**8,400**	**63,800**	**5,220**
90/60% uniform – 100% coverage	n/a	93,700	1,940,000	1,740	30,600	3,260
90/60% uniform	minimise R_{eff}	**157,000**	**2,460,000**	4,430	59,900	8,590
90% coverage	high-risk	183,000	2,590,000	**3,400**	**41,700**	**4,150**
90/60% uniform	minimise R_{eff}	**262,000**	**3,000,000**	8,900	89,400	13,300

80% coverage	high-risk	335,000	3,140,000	**6,420**	**54,400**	**4,860**
90/60% uniform	minimise R_{eff}	**404,000**	**3,440,000**	14,700	113,000	15,800
70% coverage	high-risk	483,000	3,490,000	**9,460**	**64,400**	**5,380**
80/70% uniform – 100% coverage	n/a	41,800	1,310,000	2,000	55,000	5,780
80/70% uniform	minimise R_{eff}	**95,100**	**1,930,000**	**5,170**	93,500	11,900
90% coverage	high-risk	122,000	2,090,000	5,340	**81,600**	**8,510**
80/70% uniform	minimise R_{eff}	**190,000**	**2,560,000**	**10,800**	131,000	17,500
80% coverage	high-risk	268,000	2,770,000	11,000	**105,000**	**10,600**
80/70% uniform	minimise R_{eff}	**333,000**	**3,100,000**	18,000	156,000	20,000
70% coverage	high-risk	419,000	3,190,000	**16,200**	**119,000**	**11,800**
80/60% uniform – 100% coverage	n/a	175,000	2,510,000	6,290	79,400	8,690
80/60% uniform	minimise R_{eff}	**244,000**	**2,930,000**	9,990	107,000	13,600
90% coverage	high-risk	265,000	3,000,000	**9,130**	**92,600**	**9,940**
80/60% uniform	minimise R_{eff}	**340,000**	**3,300,000**	15,500	138,000	18,600
80% coverage	high-risk	406,000	3,420,000	**13,600**	**106,000**	**10,900**
80/60% uniform	minimise R_{eff}	**475,000**	**3,650,000**	21,500	155,000	20,200
70% coverage	high-risk	543,000	3,680,000	**17,600**	**115,000**	**11,600**
70/60% uniform – 100% coverage	n/a	266,000	2,940,000	13,900	141,000	15,800
70/60% uniform	minimise R_{eff}	**336,000**	**3,280,000**	18,300	165,000	20,100
90% coverage	high-risk	354,000	3,330,000	**17,600**	**154,000**	**17,100**
70/60% uniform	minimise R_{eff}	**426,000**	**3,570,000**	23,700	187,000	23,600
80% coverage	high-risk	483,000	3,660,000	**22,900**	**166,000**	**18,100**
70/50% uniform – 100% coverage	n/a	421,000	3,520,000	17,500	136,000	15,600
70/50% uniform	minimise R_{eff}	**491,000**	**3,780,000**	21,400	154,000	19,000
90% coverage	high-risk	503,000	3,800,000	**20,200**	**144,000**	**16,300**
90/80%: age 50+ 70/60%: younger	dual vaccine	175,000	2,180,000	8,410	95,300	12,000

80% coverage		

Peak active and total community cases do not include imported cases. All measures related to hospitalisations and deaths (in all scenarios) include imported cases, which are equivalent to the expectations of 444 total hospitalisations and 49·6 total deaths.

Note: Forecasts for a two-year simulation. e_d is VE of disease prevention. e_i is VE of infection reduction. The total community cases include vaccinated cases, who are less likely to develop symptoms, need hospitalisation or die than unvaccinated individuals. A scenario of "95/90% uniform, 80% coverage" means that the vaccine has uniform effects across age groups with 95% disease prevention and 90% infection reduction, and the uptake is 80% coverage of total population. HIT is not achievable in the third and fourth scenarios, where the vaccine has poor effectiveness on infection reduction. The last scenario has 80% vaccine uptake when two vaccines are available. The "dual vaccines" strategy reused the vaccine allocation from the high-risk (group) targeting strategy. This dual strategy allocated a vaccine with lower effectiveness 70/60% for the five younger age groups and the 90/80% vaccine for the three oldest groups (aged 50 and over). Targeted vaccine strategies: (minimise R_{eff}) Targeting of younger (socialised) age groups to minimise R_{eff}; (high-risk) Groups susceptible to hospitalisation and death. Results are rounded to the third significant number. The lowest values that are at least 10% lower than other corresponding numbers of the same scenarios are in bold.

Table 2: Comparison of cases, hospitalisations and deaths when vaccination is not allocated to the 0–11 year olds (R_0=4·5) – 10 imported cases per day with two-year open borders

Vaccine scenarios (e_d/e_i, uptake, & R_0)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 84·9% coverage	n/a	17,900	413,000	388	8,310	513
95/90% uniform 80% coverage	minimise R_{eff}	**23,400**	**511,000**	**918**	18,300	2,500
	high-risk	50,600	783,000	1,140	**16,100**	**909**
95/90% uniform 70% coverage	minimise R_{eff}	**64,100**	**1,050,000**	3,510	52,400	8,070
	high-risk	157,000	1,490,000	**3,490**	**31,100**	**1,690**
95/90% uniform 60% coverage	minimise R_{eff}	**179,000**	**1,860,000**	10,000	95,900	12,500
	high-risk	310,000	2,180,000	**7,860**	**53,800**	**2,680**
95/90% uniform 50% coverage	minimise R_{eff}	**361,000**	**2,570,000**	19,500	133,000	15,500
	high-risk	508,000	2,790,000	**15,300**	**84,800**	**3,980**
95/80% uniform – 84·9% coverage	n/a	39,000	826,000	695	13,100	894
95/80% uniform 80% coverage	minimise R_{eff}	**51,000**	**1,010,000**	**1,690**	29,300	4,110
	high-risk	93,500	1,330,000	1,710	**21,700**	**1,370**
95/80% uniform 70% coverage	minimise R_{eff}	**128,000**	**1,780,000**	5,700	70,000	10,600
	high-risk	232,000	2,130,000	**4,290**	**36,400**	**2,150**
95/80% uniform 60% coverage	minimise R_{eff}	**279,000**	**2,560,000**	13,100	108,000	14,100
	high-risk	403,000	2,780,000	**8,750**	**57,200**	**3,010**
95/80% uniform 50% coverage	minimise R_{eff}	**466,000**	**3,150,000**	22,000	139,000	16,400
	high-risk	604,000	3,300,000	**16,000**	**85,700**	**4,080**
95/70% uniform – 84·9% coverage	n/a	99,200	1,730,000	1,390	21,000	1,590
95/70% uniform 80% coverage	minimise R_{eff}	**122,000**	**1,960,000**	3,200	44,100	6,300
	high-risk	174,000	2,180,000	**2,540**	**28,100**	**1,950**
95/70% uniform 70% coverage	minimise R_{eff}	**233,000**	**2,630,000**	8,400	82,700	12,500
	high-risk	331,000	2,830,000	**5,130**	**40,100**	**2,510**
95/70% uniform 60% coverage	minimise R_{eff}	**399,000**	**3,220,000**	15,700	114,000	15,000
	high-risk	506,000	3,320,000	**9,500**	**58,500**	**3,150**
95/70% uniform 50% coverage	minimise R_{eff}	**576,000**	**3,640,000**	24,100	141,000	16,800
	high-risk	698,000	3,720,000	**16,600**	**85,200**	**4,030**
90/80% uniform – 84·9% coverage	n/a	47,900	973,000	1,360	24,700	2,140
90/80% uniform 80% coverage	minimise R_{eff}	**62,700**	**1,180,000**	**2,630**	44,100	5,850
	high-risk	107,000	1,480,000	2,980	**37,700**	**3,120**
90/80% uniform	minimise R_{eff}	**148,000**	**1,950,000**	7,550	89,200	12,800

70% coverage	high-risk	250,000	2,250,000	**6,750**	**58,000**	**4,580**
90/80% uniform	minimise R_{eff}	**303,000**	**2,680,000**	15,700	128,000	16,200
60% coverage	high-risk	422,000	2,860,000	**12,200**	**81,700**	**5,930**
90/70% uniform - 84·9% coverage	n/a	123,000	1,980,000	2,860	40,300	3,690
90/70% uniform	minimise R_{eff}	**148,000**	**2,190,000**	5,020	64,900	8,660
80% coverage	high-risk	199,000	2,380,000	**4,580**	**49,200**	**4,310**
90/70% uniform	minimise R_{eff}	**262,000**	**2,800,000**	10,900	104,000	14,700
70% coverage	high-risk	356,000	2,960,000	**8,140**	**63,500**	**5,220**
90/70% uniform	minimise R_{eff}	**426,000**	**3,320,000**	18,700	134,000	17,100
60% coverage	high-risk	529,000	3,400,000	**13,200**	**82,700**	**6,130**
80/70% uniform – 84·9% coverage	n/a	184,000	2,460,000	7,790	93,900	9,670
80/70% uniform	minimise R_{eff}	**213,000**	**2,640,000**	**10,500**	118,000	14,600
80% coverage	high-risk	258,000	2,770,000	10,600	**104,000**	**10,600**
80/70% uniform	minimise R_{eff}	**327,000**	**3,100,000**	17,300	152,000	19,700
70% coverage	high-risk	411,000	3,210,000	**15,900**	**120,000**	**11,800**
80/70% uniform	minimise R_{eff}	**483,000**	**3,510,000**	25,600	178,000	21,800
60% coverage	high-risk	576,000	3,560,000	**22,000**	**137,000**	**13,000**
80/60% uniform – 84·9% coverage	n/a	328,000	3,240,000	11,100	99,500	10,500
80/60% uniform	minimise R_{eff}	**358,000**	**3,360,000**	14,400	124,000	15,500
80% coverage	high-risk	398,000	3,430,000	**13,200**	**106,000**	**11,000**
80/60% uniform	minimise R_{eff}	**468,000**	**3,660,000**	20,700	152,000	20,100
70% coverage	high-risk	537,000	3,710,000	**17,400**	**116,000**	**11,600**
80/60% uniform	minimise R_{eff}	**610,000**	**3,920,000**	27,900	173,000	21,600
60% coverage	high-risk	683,000	3,930,000	**22,500**	**130,000**	**12,300**
70/50% uniform – 84·9% coverage	n/a	555,000	3,920,000	21,900	148,000	16,700
70/50% uniform	minimise R_{eff}	**671,000**	4,160,000	31,200	189,000	24,300
70% coverage	high-risk	717,000	4,160,000	**27,500**	**159,000**	**17,400**

Note: NZ's vaccination plan has not included vaccinating 0–11 year olds.[5] The total population coverage is therefore no more than 84·9% (other age groups have a maximum coverage of 100%).[27] At the maximum total coverage (84·9%), both vaccine strategies become identical.

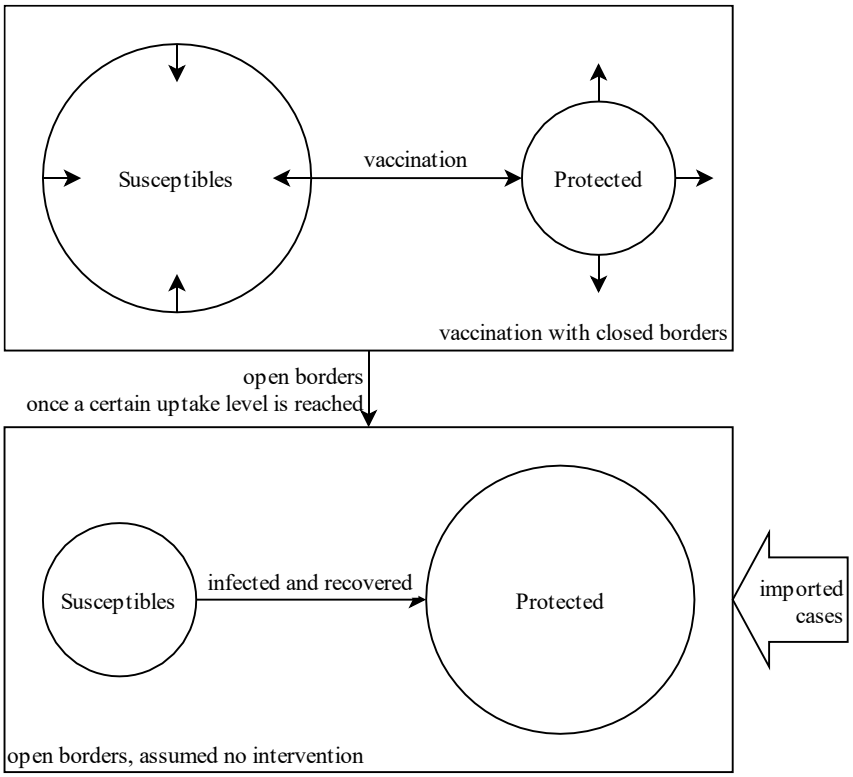


Figure 1: Pre-transmission vaccination process

Note: A level of uptake (60–100% total population) has been reached before opening borders.

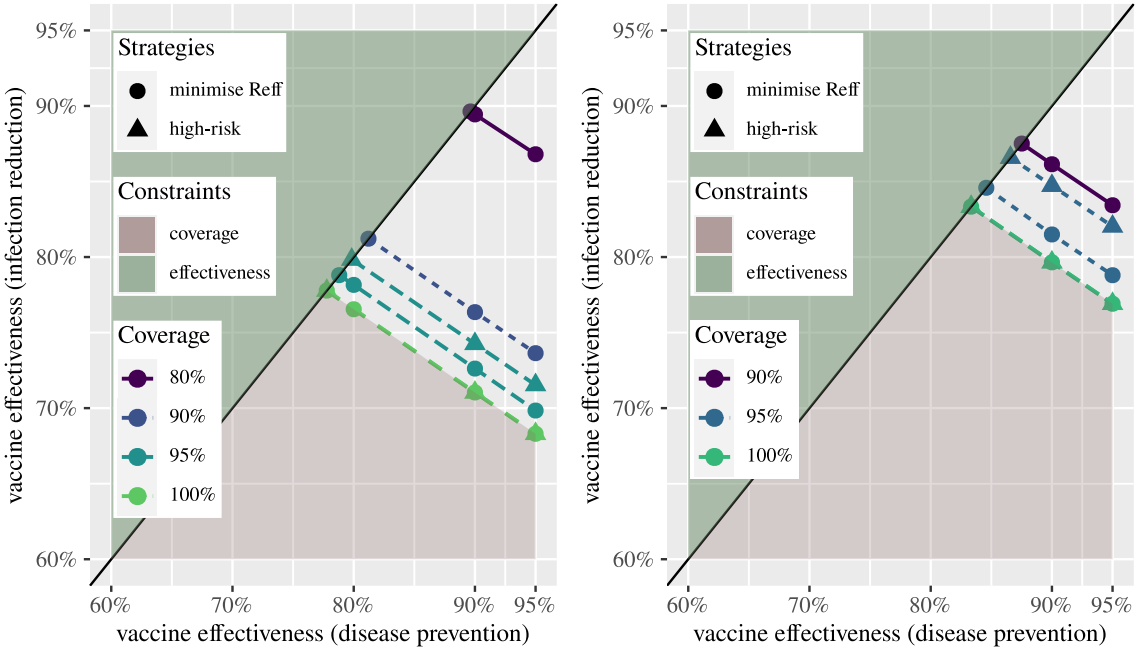


Figure 2: Vaccine effectiveness and New Zealand population vaccine uptake requirements for herd immunity threshold

Note: The minimal vaccine effectiveness on infection reduction and disease prevention for the herd immunity threshold at multiple vaccine uptake levels: (A) R_0=4·5 and (B) R_0=6. The spread-minimising strategy (i.e. minimise R_{eff}) offers lower requirements of vaccine effectiveness (on both effects) than the high-risk targeting strategy given the same uptake levels. Both effects are considered equal across age groups in this analysis. As the vaccine effectiveness on infection reduction is expected to be not greater than the vaccine effectiveness on disease prevention, all herd immunity lines are limited to the bottom half of the plot (divided by the black line).

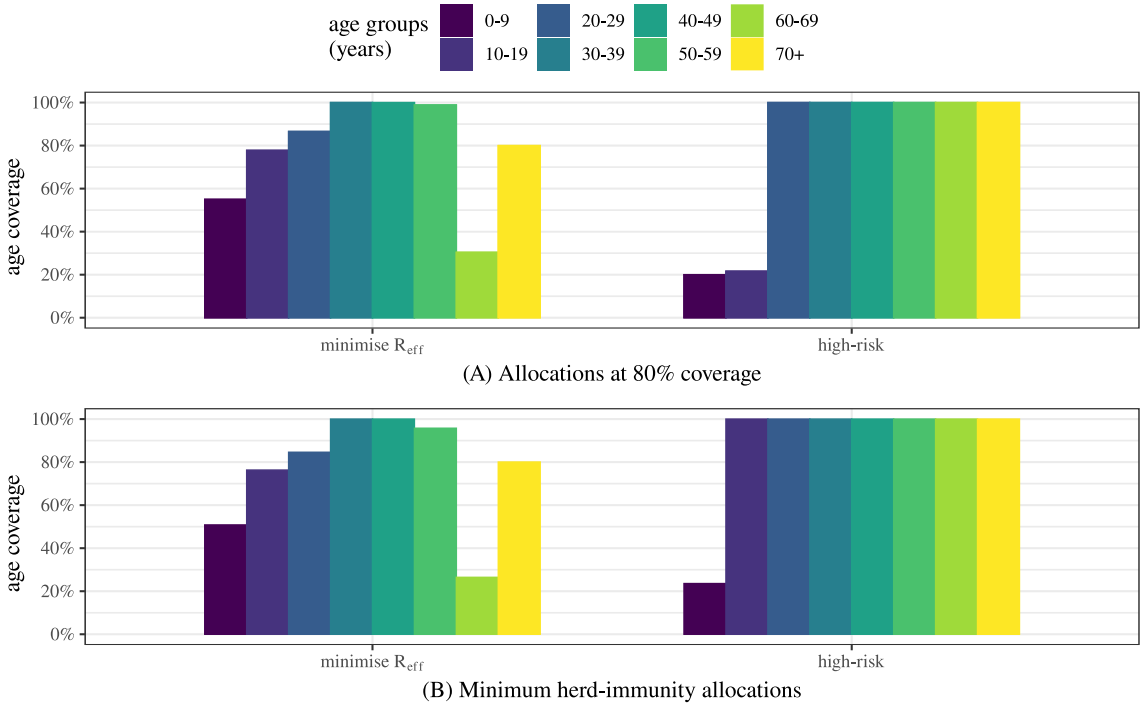


Figure 3: Age-stratified allocations for two strategies with a vaccine of 95/90% uniform effectiveness and 80% coverage (A), and their minimum herd-immunity allocations (R_0=4·5) (B).

Note: Illustration of vaccine allocations for two strategies (i.e. minimising R_{eff} and prioritising high-risk groups). A – shows 80% coverage with 95% (uniform) effectiveness on disease prevention and 90% (uniform) of infection reduction. B – shows the minimal age-stratified allocations required for HIT by the corresponding strategies. The high-risk targeting strategy requires more than 80% coverage (~90·5%) to achieve HIT, while the spread-minimising strategy needs less vaccine uptake for HIT (78·2% total coverage). For R_0=6.0 near complete coverage for all age groups is required to achieve the herd-immunity threshold.

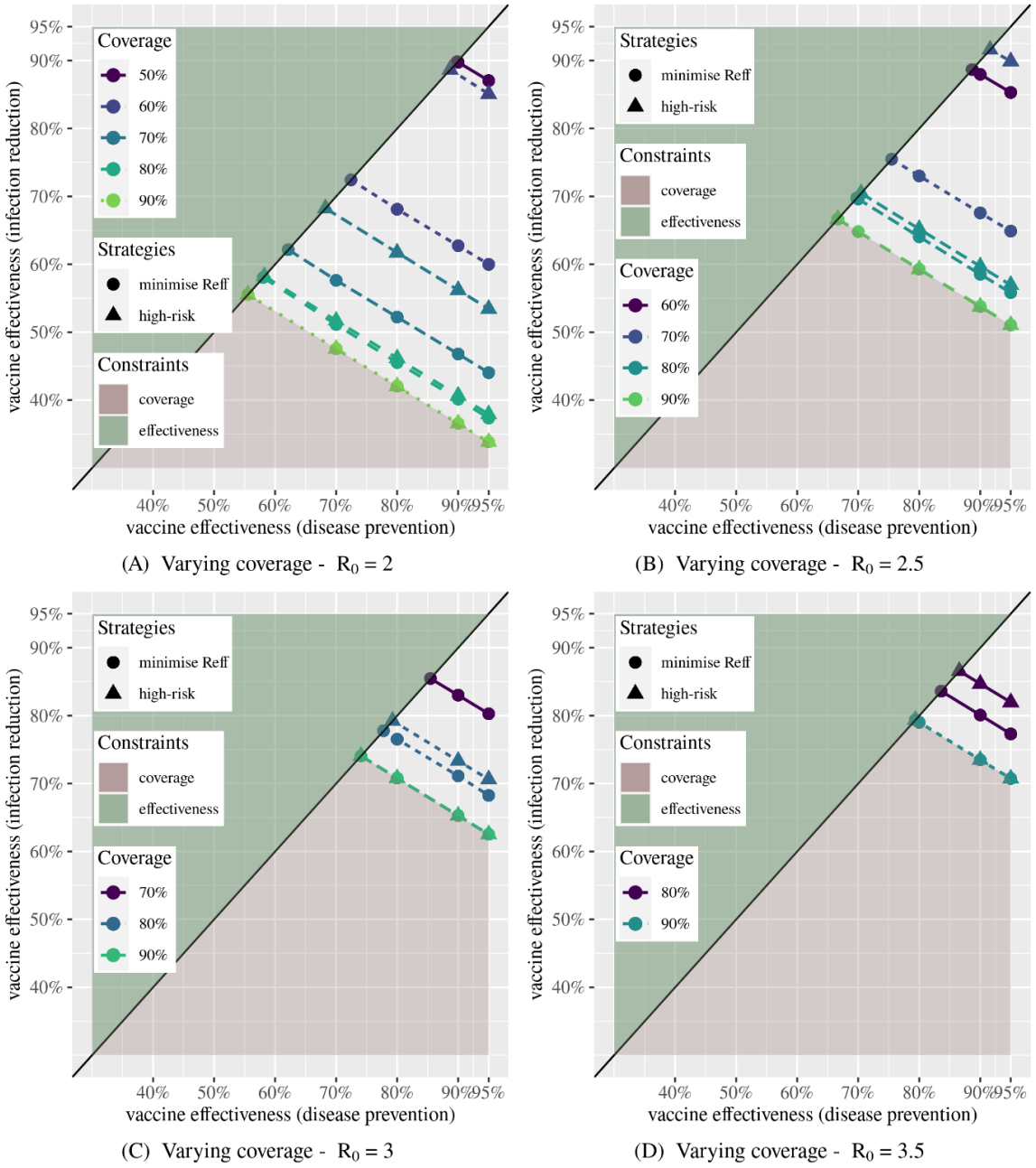


Figure 4: Vaccine effectiveness and New Zealand population vaccine uptake requirements for the herd immunity threshold at lower R_0 values

Note: The minimal vaccine effectiveness on infection reduction and disease prevention for HIT at multiple vaccine uptake levels: (A) R_0=2; (B) R_0=2·5; (C) R_0=3; and (D) R_0=3·5. The maximum vaccine coverage in each age group is 90%.

Supplementary Materials

Table S1: Parameters used in the model.

Parameter	Value	Source (Reference)
Basic reproduction number (R_0)	2·5	Assumed in reported ranges.[1-3]
Presymptomatic infectious period (t_p)	2 days	[4,5]
Latent period (not infectious) ($1/\sigma$)	3·8 days	Incubation period (5·8 days[6,7]) – presymptomatic infectious period (2 days).
Infectious period for both *Is(s)* and *Id(s)* compartments (t_d and t_s)	7·2 days	Average from symptom onset to isolation.[8]
New Zealand (NZ)/Māori and Pasifika population counts	5,000,000/ 1,224,140	[9]
Age group proportions of NZ (N_i)	0·125, 0·128, 0·141, 0·139, 0·126, 0·128, 0·106, 0·107	[9]
Relative infectiousness of subclinical cases compared with clinical cases (f)	0·5	For the same period.[10,11] The infectious durations of subclinical and clinical cases may differ.
Age stratified death rates (%)	0·0016, 0·007, 0·031, 0·084, 0·16, 0·595, 1·93, 5·48	Estimated infection fatality rate.[12]
Age stratified death rates for Māori and Pasifika populations (%)	0·01, 0·01, 0·109, 0·11, 1·22, 1·23, 7·20, 8·69	Extrapolated and combined from the estimated infection fatality rate in.[13]
Average hospitalisation period	8·9 days	EpiSurv.[14]
Hospitalisation rates (all cases without vaccination)	0·012, 0·017, 0·016, 0·048, 0·059, 0·091, 0·102, 0·24	Age-group rates.[14] Assumed double rates for Māori and Pasifika.[15]
Relative susceptibility (u_i)	0·4, 0·38, 0·79, 0·86, 0·8, 0·82, 0·88, 0·74	Age-group details.[10]
Clinical disease rates of infections (ρ_i)	0·29, 0·21, 0·27, 0·33, 0·4, 0·49, 0·63, 0·69	Age-group details.[10]
Age distribution of imported cases	0·026, 0·029, 0·327, 0·190, 0·108, 0·137, 0·127, 0·056	EpiSurv.[14]

Note: Age-group related parameters are listed in the order of increasing age i.e {0–9,10–19,20–29…,60–69,70+}. Age-stratified death rates of the combined Māori and Pasifika population are combined using their age-stratified population sizes and their corresponding separate rates estimated in.[13] The death rates for age group 70+ of the whole New Zealand (NZ) or Māori/Pasifika population are combined linearly from the death rates and population sizes (N_i) of groups 70–79 and 80+.

Table S2: Results of vaccine scenarios from a two-year open border simulation (R_0=4·5) with ten daily cases introduced to the community and vaccination allowed for 16-plus people

Vaccine scenarios (e_d/e_i, uptake, & R_0)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 79·8% coverage	n/a	53,600	804,000	1,200	16,600	931
95/90% uniform	minimise R_{eff}	**87,500**	**1,170,000**	4,210	51,700	7,600
70% coverage	high-risk	166,000	1,490,000	**3,660**	**31,400**	**1,690**
95/90% uniform	minimise R_{eff}	**184,000**	**1,870,000**	10,000	93,900	12,300
60% coverage	high-risk	313,000	2,170,000	**7,690**	**52,300**	**2,630**
95/90% uniform	minimise R_{eff}	**361,000**	**2,570,000**	19,500	133,000	15,500
50% coverage	high-risk	508,000	2,790,000	**14,900**	**82,700**	**3,880**
95/80% uniform – 79·8% coverage	n/a	97,200	1,350,000	1,780	22,100	1,400
95/80% uniform	minimise R_{eff}	**150,000**	**1,830,000**	6,110	66,200	9,830
70% coverage	high-risk	237,000	2,130,000	**4,390**	**36,500**	**2,150**
95/80% uniform	minimise R_{eff}	**282,000**	**2,570,000**	13,000	107,000	14,000
60% coverage	high-risk	403,000	2,770,000	**8,520**	**55,700**	**2,960**
95/80% uniform	minimise R_{eff}	**467,000**	**3,150,000**	22,000	139,000	16,400
50% coverage	high-risk	602,000	3,290,000	**15,600**	**83,700**	**3,990**
95/70% uniform – 79·8% coverage	n/a	178,000	2,200,000	2,610	28,400	1,970
95/70% uniform	minimise R_{eff}	**248,000**	**2,650,000**	8,350	77,700	11,600
70% coverage	high-risk	334,000	2,830,000	**5,180**	**40,200**	**2,500**
95/70% uniform	minimise R_{eff}	**400,000**	**3,220,000**	15,600	113,000	14,900
60% coverage	high-risk	504,000	3,310,000	**9,240**	**57,100**	**3,110**
95/90% uniform	minimise R_{eff}	**576,000**	**3,640,000**	24,100	141,000	16,800
70% coverage	high-risk	694,000	3,710,000	**16,100**	**83,200**	**3,950**
95/60% uniform – 79·8% coverage	n/a	295,000	3,000,000	3,530	31,900	2,310
95/60% uniform	minimise R_{eff}	**373,000**	**3,340,000**	10,500	83,000	12,500
70% coverage	high-risk	447,000	3,410,000	**5,910**	**41,400**	**2,640**
95/60% uniform	minimise R_{eff}	**523,000**	**3,710,000**	17,900	116,000	15,300
60% coverage	high-risk	607,000	3,740,000	**9,810**	**56,800**	**3,100**
90/80% uniform – 79·8% coverage	n/a	110,000	1,500,000	3,090	38,200	3,170
90/80% uniform	minimise R_{eff}	**168,000**	**1,980,000**	8,030	85,800	12,100
70% coverage	high-risk	254,000	2,250,000	**6,840**	**57,900**	**4,570**
90/80% uniform	minimise R_{eff}	**305,000**	**2,680,000**	15,700	127,000	16,200
60% coverage	high-risk	422,000	2,850,000	**12,000**	**80,200**	**5,870**
90/70% uniform – 79·8% coverage	n/a	203,000	2,400,000	4,670	49,600	4,340
90/70% uniform	minimise R_{eff}	**275,000**	**2,810,000**	10,800	98,900	13,900
70% coverage	high-risk	358,000	2,960,000	**8,190**	**63,500**	**5,210**
90/70% uniform	minimise R_{eff}	**427,000**	**3,320,000**	18,500	132,000	17,000
60% coverage	high-risk	527,000	3,400,000	**12,900**	**81,300**	**6,080**
90/60% uniform – 79·8% coverage	n/a	329,000	3,160,000	6,250	54,100	4,880
90/60% uniform	minimise R_{eff}	**405,000**	**3,460,000**	13,500	104,000	14,700
70% coverage	high-risk	476,000	3,520,000	**9,270**	**64,300**	**5,380**
90/60% uniform	minimise R_{eff}	**552,000**	**3,790,000**	21,000	134,000	17,300
60% coverage	high-risk	631,000	3,810,000	**13,600**	**79,600**	**5,970**
80/70% uniform – 79·8% coverage	n/a	262,000	2,780,000	10,700	105,000	10,600
80/70% uniform	minimise R_{eff}	**336,000**	**3,130,000**	17,300	149,000	19,200
70% coverage	high-risk	412,000	3,220,000	**15,900**	**120,000**	**11,800**
80/70% uniform	minimise R_{eff}	**484,000**	**3,510,000**	25,500	177,000	21,700
60% coverage	high-risk	574,000	3,560,000	**21,800**	**136,000**	**12,900**
80/60% uniform – 79·8% coverage	n/a	401,000	3,440,000	13,300	106,000	11,000
80/60% uniform	minimise R_{eff}	**475,000**	**3,680,000**	20,500	149,000	19,500
70% coverage	high-risk	537,000	3,710,000	**17,400**	**116,000**	**11,600**
80/60% uniform	minimise R_{eff}	**610,000**	**3,920,000**	27,800	172,000	21,500

60% coverage	high-risk	681,000	3,930,000	**22,300**	**129,000**	**12,300**
70/50% uniform – 79·8% coverage	n/a	614,000	4,030,000	24,000	153,000	17,000
70/50% uniform	minimise R_{eff}	**676,000**	4,160,000	31,000	187,000	23,900
60% coverage	high-risk	718,000	4,160,000	**27,500**	**159,000**	**17,400**

Note: Maximum vaccination coverage for each age group is now 100% (no limit). The lowest values of five measures for each scenario are in bold.

Note: e_i is the VE of reducing infection. e_d is the VE of preventing disease. The peak and total community cases do not count imported cases (7,300 cases). The peak hospitalisations, total hospitalisations, and total deaths include hospitalised and death cases from the 7,300 imported cases, which are estimated as 444 total hospitalisations and 49·6 deaths when the imported cases are assumed to be not vaccinated. A scenario of "95/70% uniform, 80% coverage" means that the vaccine has uniform effects across age groups with 95% disease prevention reduction and 70% infection reduction, and the uptake is 80% coverage of total population. Maximum vaccination coverage for each age group is now 100% (no limit). The herd immunity threshold is not achievable – no hybrid scenario, where the vaccine has poor infection reduction. Targeted vaccine strategies: (minimise R_{eff}) Targeting of younger (socialised) age groups to minimise R_{eff}; (high-risk) Groups susceptible to hospitalisation and death; (hybrid) Strategy targeting both younger age groups to achieve the herd immunity threshold and high-risk groups; and (n/a) all strategies are identical as the uptake level is at maximum 100%. Results are rounded to third significant number. The lowest values for each scenario are bold.

Table S3: Results of various vaccine scenarios from a two-year simulation (R_0=6) with daily ten cases introduced to the community and vaccination allowed all age groups

Vaccine scenarios (e_d/e_i & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 100% coverage	n/a	168	8,250	9	685	74
95/90% uniform	minimise R_{eff}	**424**	**29,200**	**30**	**2,250**	**362**
90% coverage	high-risk	24,700	440,000	571	9,520	705
	hybrid	700	50,000	33	2,320	296
95/90% uniform	minimise R_{eff}	**29,200**	**732,000**	**1,940**	43,500	7,190
80% coverage	high-risk	147,000	1,250,000	3,400	**28,100**	**1,830**
95/90% uniform	minimise R_{eff}	**166,000**	**1,700,000**	9,700	91,000	13,200
70% coverage	high-risk	296,000	1,960,000	**6,640**	**44,400**	**2,830**
95/80% uniform – 100% coverage	n/a	771	60,100	18	1,340	139
95/80% uniform	minimise R_{eff}	**15,300**	**704,000**	**654**	25,800	4,260
90% coverage	high-risk	69,500	1,210,000	1,240	**19,000**	**1,600**
95/80% uniform	minimise R_{eff}	**128,000**	**1,890,000**	5,930	75,000	12,200
80% coverage	high-risk	243,000	2,200,000	**4,420**	**37,000**	**2,710**
95/80% uniform	minimise R_{eff}	**313,000**	**2,710,000**	13,400	103,000	14,900
70% coverage	high-risk	426,000	2,840,000	**7,750**	**50,100**	**3,460**
95/70% uniform – 100% coverage	n/a	70,300	1,710,000	877	18,100	1,910
95/70% uniform	minimise R_{eff}	**158,000**	**2,420,000**	4,290	56,100	9,010
90% coverage	high-risk	205,000	2,580,000	**2,670**	**29,500**	**2,710**
95/70% uniform	minimise R_{eff}	**301,000**	**3,060,000**	9,980	86,900	14,000
80% coverage	high-risk	396,000	3,200,000	**5,600**	**41,600**	**3,240**
95/70% uniform	minimise R_{eff}	**490,000**	**3,540,000**	16,800	108,000	15,800
70% coverage	high-risk	579,000	3,570,000	**8,630**	**51,100**	**3,650**
95/60% uniform – 100% coverage	n/a	262,000	3,000,000	2,410	24,000	2,660
95/60% uniform	minimise R_{eff}	**364,000**	**3,430,000**	7,010	58,000	9,220
90% coverage	high-risk	397,000	3,500,000	**4,000**	**31,600**	**3,010**
95/60% uniform	minimise R_{eff}	**500,000**	**3,780,000**	13,000	87,500	14,100
80% coverage	high-risk	572,000	3,850,000	**6,540**	**41,200**	**3,270**
95/60% uniform	minimise R_{eff}	**667,000**	4,070,000	19,300	108,000	15,900
70% coverage	high-risk	731,000	**4,050,000**	**9,190**	**49,400**	**3,530**
90/80% uniform – 100% coverage	n/a	2,380	164,000	89	5,400	551
90/80% uniform	minimise R_{eff}	**39,700**	**1,210,000**	**2,070**	54,900	8,020
90% coverage	high-risk	91,400	1,530,000	2,900	**43,000**	**4,190**
90/80% uniform	minimise R_{eff}	**164,000**	**2,180,000**	8,780	103,000	15,200
80% coverage	high-risk	269,000	2,430,000	**7,930**	**67,800**	**6,200**
90/80% uniform	minimise R_{eff}	**349,000**	**2,880,000**	17,100	130,000	17,800
70% coverage	high-risk	453,000	2,980,000	**12,700**	**83,900**	**7,390**
90/70% uniform – 100% coverage	n/a	119,000	2,150,000	2,920	45,100	4,850
90/70% uniform	minimise R_{eff}	**213,000**	**2,750,000**	7,320	82,600	11,700
90% coverage	high-risk	253,000	2,860,000	**5,960**	**59,600**	**6,100**
90/70% uniform	minimise R_{eff}	**351,000**	**3,260,000**	13,800	114,000	16,800
80% coverage	high-risk	436,000	3,380,000	**10,100**	**73,200**	**6,950**
90/70% uniform	minimise R_{eff}	**531,000**	**3,670,000**	21,000	134,000	18,400
70% coverage	high-risk	613,000	3,690,000	**14,000**	**83,100**	**7,510**

90/60% uniform – 100% coverage	n/a	321,000	3,230,000	5,800	51,400	5,780
90/60% uniform	minimise R_{eff}	**420,000**	**3,600,000**	11,000	84,900	12,200
90% coverage	high-risk	451,000	3,660,000	**8,150**	**60,200**	**6,350**
90/60% uniform	minimise R_{eff}	**548,000**	**3,900,000**	17,200	113,000	16,800
80% coverage	high-risk	616,000	3,960,000	**11,500**	**70,100**	**6,760**
90/60% uniform	minimise R_{eff}	**708,000**	4,140,000	23,500	131,000	18,400
70% coverage	high-risk	766,000	**4,130,000**	**14,500**	**78,000**	**7,090**
80/70% uniform – 100% coverage	n/a	235,000	2,810,000	11,100	119,000	13,200
80/70% uniform	minimise R_{eff}	**333,000**	**3,250,000**	16,900	152,000	19,100
90% coverage	high-risk	361,000	3,310,000	**15,900**	**135,000**	**14,800**
80/70% uniform	minimise R_{eff}	**450,000**	**3,580,000**	23,800	178,000	23,400
80% coverage	high-risk	526,000	3,690,000	**22,000**	**148,000**	**15,900**
80/70% uniform	minimise R_{eff}	**617,000**	3,890,000	31,400	193,000	24,600
70% coverage	high-risk	684,000	3,890,000	**26,900**	**156,000**	**16,500**
80/60% uniform – 100% coverage	n/a	441,000	3,590,000	15,400	115,000	13,300
80/60% uniform	minimise R_{eff}	**537,000**	**3,880,000**	21,000	142,000	18,400
90% coverage	high-risk	561,000	3,920,000	**18,800**	**124,000**	**14,000**
80/60% uniform	minimise R_{eff}	**648,000**	**4,100,000**	27,200	166,000	22,300
80% coverage	high-risk	707,000	4,140,000	**23,200**	**133,000**	**14,600**
80/60% uniform	minimise R_{eff}	**790,000**	4,280,000	33,700	181,000	23,800
70% coverage	high-risk	838,000	**4,260,000**	**26,800**	**140,000**	**14,900**
70/60% uniform – 100% coverage	n/a	560,000	3,860,000	28,300	187,000	22,000
70/60% uniform	minimise R_{eff}	**651,000**	**4,090,000**	33,800	208,000	25,900
90% coverage	high-risk	670,000	4,120,000	**32,200**	**195,000**	**22,800**
70/60% uniform	minimise R_{eff}	**746,000**	**4,250,000**	39,200	223,000	28,400
80% coverage	high-risk	800,000	4,290,000	**37,200**	**202,000**	**23,300**
70/50% uniform – 100% coverage	n/a	734,000	4,210,000	29,300	165,000	19,800
70/50% uniform	minimise R_{eff}	**819,000**	4,390,000	34,300	183,000	23,300
90% coverage	high-risk	831,000	4,390,000	**32,100**	**171,000**	**20,200**

Note: Maximum vaccination coverage for each age group is now 100% (no limit). The lowest values of five measures for each scenario are in bold.

Table S4: Results of various vaccine scenarios from a two-year simulation (R_0=6) with daily ten cases introduced to the community and vaccination allowed for 12-plus people

Vaccine scenarios (e_d/e_i, uptake, & R_0)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 84·9% coverage	n/a	73,100	830,000	1,660	17,800	1,260
95/90% uniform 80% coverage	minimise R_{eff}	91,700	1,020,000	3,690	38,100	5,230
	high-risk	138,000	1,240,000	3,160	27,400	1,820
95/90% uniform 70% coverage	minimise R_{eff}	186,000	1,700,000	9,700	82,400	12,500
	high-risk	292,000	1,960,000	6,490	44,000	2,810
95/90% uniform 60% coverage	minimise R_{eff}	360,000	2,430,000	18,800	122,000	15,900
	high-risk	487,000	2,590,000	12,100	67,200	3,940
95/90% uniform 50% coverage	minimise R_{eff}	579,000	3,020,000	29,300	153,000	18,100
	high-risk	713,000	3,130,000	20,600	97,300	5,300
95/80% uniform – 84·9% coverage	n/a	145,000	1,760,000	2,580	28,100	2,240
95/80% uniform 80% coverage	minimise R_{eff}	177,000	2,010,000	5,670	56,100	7,920
	high-risk	236,000	2,200,000	4,240	36,400	2,720
95/80% uniform 70% coverage	minimise R_{eff}	315,000	2,690,000	12,900	97,300	14,500
	high-risk	420,000	2,850,000	7,580	49,800	3,450
95/80% uniform 60% coverage	minimise R_{eff}	514,000	3,270,000	21,800	128,000	16,800
	high-risk	624,000	3,340,000	12,900	69,200	4,240
95/80% uniform 50% coverage	minimise R_{eff}	723,000	3,690,000	31,400	155,000	18,500
	high-risk	842,000	3,730,000	21,000	96,000	5,250
95/70% uniform – 84·9% coverage	n/a	295,000	2,940,000	3,980	35,400	3,020
95/70% uniform 80% coverage	minimise R_{eff}	336,000	3,130,000	8,150	66,200	9,460
	high-risk	392,000	3,210,000	5,480	41,100	3,250
95/70% uniform 70% coverage	minimise R_{eff}	486,000	3,550,000	15,800	103,000	15,400
	high-risk	574,000	3,600,000	8,480	50,900	3,640
95/70% uniform 60% coverage	minimise R_{eff}	677,000	3,900,000	24,200	129,000	17,100
	high-risk	764,000	3,890,000	13,500	67,900	4,170
95/70% uniform 50% coverage	minimise R_{eff}	862,000	4,150,000	33,000	154,000	18,600
	high-risk	962,000	4,150,000	21,300	93,200	4,960
90/80% uniform – 84·9% coverage	n/a	170,000	2,030,000	5,190	56,400	5,360
90/80% uniform 80% coverage	minimise R_{eff}	205,000	2,270,000	8,660	85,900	11,300
	high-risk	263,000	2,430,000	7,730	67,300	6,210
90/80% uniform 70% coverage	minimise R_{eff}	348,000	2,870,000	16,600	126,000	17,500
	high-risk	447,000	3,000,000	12,500	83,900	7,420
90/80% uniform 60% coverage	minimise R_{eff}	544,000	3,380,000	26,200	156,000	19,800
	high-risk	648,000	3,430,000	18,700	104,000	8,540
90/70% uniform – 84·9% coverage	n/a	340,000	3,160,000	7,910	66,600	6,600
90/70% uniform 80% coverage	minimise R_{eff}	381,000	3,320,000	12,200	96,300	12,800
	high-risk	433,000	3,390,000	9,970	72,900	6,970
90/70% uniform 70% coverage	minimise R_{eff}	527,000	3,680,000	20,100	130,000	18,100
	high-risk	609,000	3,720,000	13,800	83,200	7,530
90/70% uniform 60% coverage	minimise R_{eff}	710,000	3,980,000	28,600	154,000	19,800
	high-risk	792,000	3,970,000	19,200	99,200	8,190
80/70% uniform – 84·9% coverage	n/a	441,000	3,530,000	18,800	142,000	15,400
80/70% uniform 80% coverage	minimise R_{eff}	480,000	3,660,000	23,100	166,000	20,600
	high-risk	524,000	3,700,000	21,700	148,000	15,900
80/70% uniform 70% coverage	minimise R_{eff}	612,000	3,910,000	30,600	191,000	24,400
	high-risk	683,000	3,930,000	26,800	156,000	16,600
80/70% uniform 60% coverage	minimise R_{eff}	778,000	4,120,000	38,700	208,000	25,700
	high-risk	850,000	4,100,000	32,600	168,000	17,200
80/60% uniform – 84·9% coverage	n/a	633,000	4,050,000	20,900	129,000	14,400
80/60% uniform	minimise R_{eff}	670,000	4,140,000	25,700	154,000	19,700

80% coverage	high-risk	706,000	4,160,000	23,000	133,000	14,600
80/60% uniform	minimise R_{eff}	785,000	4,300,000	32,700	177,000	23,500
70% coverage	high-risk	839,000	4,290,000	26,700	140,000	15,000
80/60% uniform	minimise R_{eff}	926,000	4,430,000	39,800	194,000	24,600
60% coverage	high-risk	978,000	4,390,000	31,600	151,000	15,400
70/50% uniform – 84·9% coverage	n/a	888,000	4,460,000	33,800	174,000	20,400
70/50% uniform	minimise R_{eff}	1,010,000	4,600,000	44,200	211,000	27,500
70% coverage	high-risk	1,040,000	4,580,000	38,700	181,000	20,800

Note: Maximum vaccination coverage for each age group is now 100% (no limit). The lowest values of five measures for each scenario are in bold.

Table S5: Results of various vaccine scenarios from a two-year simulation (R_0=6) with daily ten cases introduced to the community and vaccination allowed for 16-plus people

Vaccine scenarios (e_d/e_i, uptake, & R_0)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 79·8% coverage	n/a	143,000	1,260,000	3,250	27,800	1,850
95/90% uniform 70% coverage	minimise R_{eff}	215,000	1,740,000	10,300	79,300	11,800
	high-risk	296,000	1,950,000	6,570	43,900	2,800
95/90% uniform 60% coverage	minimise R_{eff}	365,000	2,430,000	18,700	120,000	15,700
	high-risk	487,000	2,580,000	11,800	65,500	3,870
95/90% uniform 50% coverage	minimise R_{eff}	579,000	3,030,000	29,300	153,000	18,000
	high-risk	712,000	3,120,000	20,100	95,200	5,200
95/80% uniform – 79·8% coverage	n/a	241,000	2,220,000	4,330	36,800	2,740
95/80% uniform 70% coverage	minimise R_{eff}	336,000	2,710,000	12,800	92,100	13,600
	high-risk	420,000	2,840,000	7,600	49,800	3,440
95/80% uniform 60% coverage	minimise R_{eff}	516,000	3,270,000	21,500	126,000	16,600
	high-risk	622,000	3,330,000	12,600	67,700	4,190
95/80% uniform 50% coverage	minimise R_{eff}	723,000	3,690,000	31,400	155,000	18,500
	high-risk	840,000	3,730,000	20,500	94,100	5,160
95/70% uniform – 79·8% coverage	n/a	396,000	3,220,000	5,550	41,300	3,260
95/70% uniform 70% coverage	minimise R_{eff}	499,000	3,560,000	15,300	97,000	14,400
	high-risk	573,000	3,600,000	8,480	51,000	3,640
95/70% uniform 60% coverage	minimise R_{eff}	678,000	3,900,000	23,900	128,000	17,000
	high-risk	761,000	3,890,000	13,100	66,400	4,130
95/70% uniform 50% coverage	minimise R_{eff}	862,000	4,150,000	33,000	154,000	18,600
	high-risk	959,000	4,140,000	20,700	91,300	4,880
95/60% uniform – 79·8% coverage	n/a	572,000	3,870,000	6,480	40,900	3,280
95/60% uniform 70% coverage	minimise R_{eff}	670,000	4,090,000	17,300	96,900	14,600
	high-risk	728,000	4,080,000	9,070	49,300	3,510
95/60% uniform 60% coverage	minimise R_{eff}	829,000	4,280,000	25,900	127,000	17,100
	high-risk	890,000	4,250,000	13,400	63,800	3,880
90/80% uniform – 79·8% coverage	n/a	268,000	2,440,000	7,850	67,800	6,250
90/80% uniform 70% coverage	minimise R_{eff}	365,000	2,890,000	16,700	122,000	16,700
	high-risk	447,000	3,000,000	12,500	83,800	7,410
90/80% uniform 60% coverage	minimise R_{eff}	546,000	3,390,000	26,000	155,000	19,600
	high-risk	646,000	3,430,000	18,400	103,000	8,490
90/70% uniform – 79·8% coverage	n/a	437,000	3,400,000	10,100	73,100	6,990
90/70% uniform 70% coverage	minimise R_{eff}	538,000	3,700,000	19,700	125,000	17,400
	high-risk	607,000	3,720,000	13,800	83,300	7,530
90/70% uniform 60% coverage	minimise R_{eff}	711,000	3,980,000	28,500	153,000	19,800
	high-risk	789,000	3,970,000	18,900	98,000	8,150
90/60% uniform – 79·8% coverage	n/a	617,000	3,980,000	11,400	69,900	6,780
90/60% uniform 70% coverage	minimise R_{eff}	710,000	4,170,000	21,800	122,000	17,200
	high-risk	764,000	4,160,000	14,400	78,000	7,090
90/60% uniform 60% coverage	minimise R_{eff}	861,000	4,330,000	30,200	149,000	19,500
	high-risk	918,000	4,300,000	19,000	91,600	7,520
80/70% uniform – 79·8% coverage	n/a	528,000	3,710,000	21,900	148,000	15,900
80/70% uniform 70% coverage	minimise R_{eff}	620,000	3,930,000	30,400	188,000	24,000
	high-risk	681,000	3,930,000	26,800	157,000	16,600
80/70% uniform 60% coverage	minimise R_{eff}	778,000	4,120,000	38,700	208,000	25,700
	high-risk	846,000	4,110,000	32,300	168,000	17,200
80/60% uniform – 79·8% coverage	n/a	709,000	4,160,000	23,100	133,000	14,600
80/60% uniform 70% coverage	minimise R_{eff}	793,000	4,310,000	32,300	174,000	22,900
	high-risk	838,000	4,290,000	26,800	140,000	15,000

80/60% uniform 60% coverage	minimise R_{eff}	926,000	4,420,000	39,800	195,000	24,600
	high-risk	976,000	4,400,000	31,300	151,000	15,400
70/50% uniform – 79·8% coverage	n/a	946,000	4,520,000	35,600	177,000	20,600
70/50% uniform 60% coverage	minimise R_{eff}	1,010,000	4,600,000	43,900	209,000	27,200
	high-risk	1,040,000	4,580,000	38,700	182,000	20,800

Note: Maximum vaccination coverage for each age group is now 100% (no limit). The lowest values of five measures for each scenario are in bold.

Table S6: Results of various vaccine scenarios from a two-year simulation (R_0=2·5) with daily ten cases introduced to the community and vaccination allowed for all age groups

Vaccine scenarios (e_d/e_i & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 90% coverage	n/a	144	5,860	9	707	76
95/90% uniform 80% coverage	minimise R_{eff}	190	9,720	13	1,000	127
	high-risk	188	9,660	10	800	83
	hybrid	188	9,660	10	800	83
95/90% uniform 70% coverage	minimise R_{eff}	310	19,800	21	1,590	219
	high-risk	1,120	72,000	39	2,450	192
	hybrid	458	31,700	20	1,530	133
95/90% uniform 60% coverage	minimise R_{eff}	1,310	90,700	86	5,630	707
	high-risk	26,200	734,000	852	21,300	1,380
	hybrid	2,020	133,000	123	7,550	867
95/80% uniform – 90% coverage	n/a	205	11,500	10	795	85
95/80% uniform 80% coverage	minimise R_{eff}	279	17,800	16	1,210	156
	high-risk	281	18,100	12	946	96
	hybrid	281	18,100	12	946	96
95/80% uniform 70% coverage	minimise R_{eff}	506	35,900	29	2,180	305
	high-risk	3,450	201,000	103	5,330	406
	hybrid	928	66,900	38	2,630	234
95/80% uniform 60% coverage	minimise R_{eff}	5,950	340,000	333	17,000	2,140
	high-risk	46,900	1,070,000	1,380	27,800	1,860
95/70% uniform – 90% coverage	n/a	327	22,600	12	969	102
95/70% uniform 80% coverage	minimise R_{eff}	483	35,300	21	1,610	205
	high-risk	509	37,500	17	1,280	128
	hybrid	509	37,500	17	1,280	128
95/70% uniform 70% coverage	minimise R_{eff}	1,270	92,100	62	4,190	599
	high-risk	11,600	531,000	300	11,900	930
	hybrid	1,880	131,000	77	4,840	601
95/70% uniform 60% coverage	minimise R_{eff}	24,300	911,000	1,200	39,400	4,940
	high-risk	76,600	1,460,000	2,040	34,000	2,360
95/60% uniform – 90% coverage	n/a	697	53,600	20	1,450	151
95/60% uniform 80% coverage	minimise R_{eff}	1,370	102,000	47	3,160	405
	high-risk	1,600	117,000	40	2,630	253
	hybrid	1,570	115,000	43	2,830	296
95/60% uniform 70% coverage	minimise R_{eff}	7,940	456,000	325	16,200	2,330
	high-risk	32,100	1,040,000	727	20,200	1,640
95/60% uniform 60% coverage	minimise R_{eff}	59,800	1,490,000	2,530	55,200	6,950
	high-risk	115,000	1,870,000	2,770	39,400	2,820
95/50% uniform – 90% coverage	n/a	3,830	258,000	78	4,480	458
95/50% uniform 80% coverage	minimise R_{eff}	11,300	612,000	290	13,400	1,690
	high-risk	13,400	693,000	261	11,500	1,100
95/50% uniform 70% coverage	minimise R_{eff}	38,100	1,270,000	1,290	37,000	5,250
	high-risk	68,800	1,600,000	1,370	27,400	2,300
95/40% uniform – 90% coverage	n/a	29,700	1,100,000	485	15,200	1,580
95/40% uniform 80% coverage	minimise R_{eff}	49,800	1,460,000	975	24,300	2,870
	high-risk	53,400	1,510,000	892	21,500	2,090

90/80% uniform – 90% coverage	n/a	220	12,600	12	956	101
90/80% uniform 80% coverage	minimise R_{eff}	304	19,600	18	1,410	175
	high-risk	311	20,300	15	1,170	119
	hybrid	311	20,300	15	1,170	119
90/80% uniform 70% coverage	minimise R_{eff}	599	42,600	38	2,730	374
	high-risk	4,680	257,000	166	8,080	662
	hybrid	1,030	73,100	51	3,470	343
90/70% uniform – 90% coverage	n/a	371	26,100	16	1,250	130
90/70% uniform 80% coverage	minimise R_{eff}	580	42,600	29	2,110	264
	high-risk	619	45,700	24	1,760	175
	hybrid	618	45,700	24	1,760	175
90/70% uniform 70% coverage	minimise R_{eff}	1,840	128,000	98	6,210	864
	high-risk	15,400	640,000	483	17,500	1,480
	hybrid	2,440	163,000	120	7,200	934
90/60% uniform – 90% coverage	n/a	930	70,600	31	2,190	226
90/60% uniform 80% coverage	minimise R_{eff}	2,160	152,000	81	5,050	614
	high-risk	2,650	181,000	80	4,770	466
	hybrid	2,480	171,000	89	5,450	636
90/60% uniform 70% coverage	minimise R_{eff}	13,100	663,000	590	25,900	3,600
	high-risk	40,200	1,170,000	1,120	28,300	2,470
90/50% uniform – 90% coverage	n/a	7,390	438,000	188	9,490	972
90/50% uniform 80% coverage	minimise R_{eff}	19,000	862,000	553	21,500	2,530
	high-risk	21,500	932,000	531	19,600	1,940
90/50% uniform 70% coverage	minimise R_{eff}	50,000	1,450,000	1,900	47,700	6,550
	high-risk	81,200	1,740,000	2,000	37,100	3,330
90/40% uniform – 90% coverage	n/a	42,300	1,310,000	902	23,700	2,490
90/40% uniform 80% coverage	minimise R_{eff}	64,700	1,650,000	1,520	33,100	3,750
	high-risk	68,400	1,690,000	1,470	31,000	3,110
80/70% uniform – 90% coverage	n/a	525	37,500	29	2,160	224
8070% uniform 80% coverage	minimise R_{eff}	968	69,700	57	3,950	470
	high-risk	1,100	78,400	55	3,710	373
	hybrid	1,100	78,300	55	3,710	373
80/70% uniform 70% coverage	minimise R_{eff}	5,130	303,000	319	16,900	2,230
	high-risk	26,100	883,000	1,130	33,800	3,150
80/60% uniform – 90% coverage	n/a	2,340	159,000	104	6,300	644
80/60% uniform 80% coverage	minimise R_{eff}	7,510	428,000	365	18,100	2,140
	high-risk	9,030	497,000	373	17,800	1,780
80/60% uniform 70% coverage	minimise R_{eff}	29,600	1,090,000	1,570	50,800	6,610
	high-risk	60,100	1,450,000	2,310	49,100	4,690
70/50% uniform – 90% coverage	n/a	47,100	1,340,000	2,250	56,200	5,940
70/50% uniform 80% coverage	minimise R_{eff}	70,800	1,680,000	3,380	70,700	7,800
	high-risk	74,600	1,720,000	3,420	69,500	7,290
70/30% uniform – 90% coverage	n/a	184,000	2,540,000	6,610	80,300	8,820

Note: e_i is the VE of reducing infection. e_d is the VE of preventing disease. The peak and total community cases do not count imported cases (7,300 cases). The peak hospitalisations, total hospitalisations, and total deaths include hospitalised and death cases from the 7,300 imported cases, which are estimated as 444 total hospitalisations and 84 deaths when the imported cases are assumed to be not vaccinated. A scenario of "95/70% uniform, 80% coverage" means that the vaccine has uniform effects across age groups with 95% disease

prevention reduction and 70% infection reduction, and the uptake is 80% coverage of total population. The herd immunity threshold is not achievable – no hybrid scenario, where the vaccine has poor infection reduction. Targeted vaccine strategies: (minimise R_{eff}) Targeting of younger (socialised) age groups to minimise R_{eff}; (high-risk) Groups susceptible to hospitalisation and death; (hybrid) Strategy targeting both younger age groups to achieve the herd immunity threshold and high-risk groups; and (n/a) all strategies are identical as the uptake level is at maximum 90%. Results are rounded to third significant number. The lowest values for each scenario are in bold.

Table S7: Results of various vaccine scenarios from a two-year simulation (R_0=2·5) with daily ten cases introduced to the community and vaccination allowed only for people aged at least 12

Vaccine scenarios (e_d/e_i & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 76·4% coverage	n/a	233	13,500	11	893	90
95/90% uniform 70% coverage	minimise R_{eff}	316	20,100	19	1,450	188
	high-risk	991	63,700	35	2,210	177
	hybrid	429	29,300	18	1,330	120
95/90% uniform 60% coverage	minimise R_{eff}	1,120	77,500	69	4,600	593
	high-risk	21,000	661,000	636	17,900	1,210
	hybrid	1,700	114,000	98	6,100	688
95/80% uniform – 76·4% coverage	n/a	368	25,200	14	1,110	109
95/80% uniform 70% coverage	minimise R_{eff}	540	38,400	28	2,030	267
	high-risk	2,840	169,000	85	4,530	351
	hybrid	865	62,200	33	2,270	196
95/80% uniform 60% coverage	minimise R_{eff}	4,340	262,000	234	12,600	1,630
	high-risk	38,300	976,000	1,050	23,700	1,660
95/70% uniform – 76·4% coverage	n/a	766	56,800	24	1,680	160
95/70% uniform 70% coverage	minimise R_{eff}	1,400	100,000	60	3,940	526
	high-risk	9,400	462,000	243	10,400	817
	hybrid	1,710	120,000	68	4,310	535
95/70% uniform 60% coverage	minimise R_{eff}	19,200	811,000	899	33,300	4,300
	high-risk	64,500	1,360,000	1,600	29,700	2,160
95/60% uniform – 76·4% coverage	n/a	3,480	228,000	82	4,670	429
95/60% uniform 70% coverage	minimise R_{eff}	8,520	481,000	305	14,900	2,010
	high-risk	27,000	958,000	610	18,600	1,520
95/60% uniform 60% coverage	minimise R_{eff}	51,600	1,420,000	2,100	50,200	6,480
	high-risk	101,000	1,790,000	2,260	35,100	2,630
90/80% uniform – 76·4% coverage	n/a	419	28,900	19	1,410	140
90/80% uniform 70% coverage	minimise R_{eff}	641	45,600	36	2,590	335
	high-risk	3,810	216,000	135	6,820	568
	hybrid	974	69,000	44	2,970	291
90/80% uniform 60% coverage	minimise R_{eff}	6,620	368,000	384	19,100	2,430
	high-risk	43,900	1,050,000	1,450	30,800	2,400
90/70% uniform – 76·4% coverage	n/a	1,010	73,200	36	2,470	238
90/70% uniform 70% coverage	minimise R_{eff}	2,070	140,000	98	6,050	792
	high-risk	12,500	566,000	393	15,500	1,320
	hybrid	2,480	164,000	115	6,890	881
90/70% uniform 60% coverage	minimise R_{eff}	25,900	960,000	1,310	42,900	5,420
	high-risk	72,800	1,450,000	2,180	38,400	3,080
90/60% uniform – 76·4% coverage	n/a	6,090	364,000	175	9,030	855
90/60% uniform 70% coverage	minimise R_{eff}	13,700	685,000	554	23,900	3,130
	high-risk	34,300	1,100,000	950	26,300	2,330
90/60% uniform 60% coverage	minimise R_{eff}	62,700	1,550,000	2,800	60,800	7,660
	high-risk	112,000	1,880,000	3,030	45,000	3,720
80/70% uniform – 76·4% coverage	n/a	2,270	149,000	107	6,340	625
80/70% uniform 70% coverage	minimise R_{eff}	5,690	329,000	326	16,800	2,100
	high-risk	21,700	805,000	937	30,800	2,890

80/70% uniform 60% coverage	minimise R_{eff}	42,900	1,250,000	2,510	65,300	7,960
	high-risk	91,700	1,640,000	3,720	59,800	5,400
80/60% uniform – 76·4% coverage	n/a	17,000	784,000	682	27,400	2,720
80/60% uniform 70% coverage	minimise R_{eff}	30,100	1,100,000	1,480	47,700	5,930
	high-risk	52,700	1,380,000	2,030	46,800	4,500
80/60% uniform 60% coverage	minimise R_{eff}	87,800	1,820,000	4,540	83,600	10,200
	high-risk	136,000	2,080,000	5,010	68,500	6,320

Note: The smallest values in each scenario are bold. Age group coverage is limited to be not greater than 90%. Total attainable vaccine coverage is, therefore, 76·4%.

Table S8: Results of various vaccine scenarios from a two-year simulation (R_0=2·5) where vaccine is only allowed for people aged at least 16 – daily ten cases introduced to the community

Vaccine scenarios (e_d/e_i, uptake, & R_0)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 71·8% coverage	n/a	392	25,900	16	1,220	111
95/90% uniform 70% coverage	minimise R_{eff}	**434**	**29,100**	**19**	**1,390**	**138**
	high-risk	991	63,700	35	2,210	177
	hybrid	490	33,400	20	1,420	125
95/90% uniform 60% coverage	minimise R_{eff}	**1,310**	**88,200**	**76**	**4,860**	**627**
	high-risk	24,200	695,000	731	18,800	1,260
	hybrid	1,790	117,000	99	6,080	709
95/90% uniform 50% coverage	minimise R_{eff}	**28,500**	**881,000**	**1,750**	48,700	5,550
	high-risk	102,000	1,510,000	3,570	**47,500**	**2,770**
95/80% uniform – 71·8% coverage	n/a	833	58,300	28	1,900	165
95/80% uniform 70% coverage	minimise R_{eff}	**910**	**63,500**	**34**	**2,260**	232
	high-risk	2,840	169,000	85	4,530	351
	hybrid	1,010	70,300	36	2,370	**227**
95/80% uniform 60% coverage	minimise R_{eff}	**5,150**	**298,000**	**261**	**13,500**	1,750
	high-risk	40,800	993,000	1,120	24,100	**1,680**
95/80% uniform 50% coverage	minimise R_{eff}	**55,900**	**1,310,000**	**3,070**	63,900	7,290
	high-risk	134,000	1,830,000	4,300	**52,400**	**3,140**
95/70% uniform – 71·8% coverage	n/a	3,180	199,000	85	4,700	392
95/70% uniform 70% coverage	minimise R_{eff}	**3,760**	**231,000**	**113**	**6,100**	**609**
	high-risk	9,400	462,000	243	10,400	817
95/70% uniform 60% coverage	minimise R_{eff}	**20,100**	**827,000**	**907**	32,700	4,240
	high-risk	66,000	1,370,000	1,640	**29,800**	**2,160**
95/70% uniform 50% coverage	minimise R_{eff}	**93,600**	**1,750,000**	**4,580**	75,900	8,700
	high-risk	172,000	2,160,000	5,060	**56,600**	**3,470**
95/60% uniform – 71·8% coverage	n/a	15,400	718,000	349	13,900	1,180
95/60% uniform 60% coverage	minimise R_{eff}	**51,900**	**1,420,000**	**2,090**	49,700	6,430
	high-risk	101,000	1,790,000	2,280	**35,100**	**2,630**
90/80% uniform – 71·8% coverage	n/a	1,080	73,600	41	2,700	243
90/80% uniform 60% coverage	minimise R_{eff}	**7,560**	**404,000**	**421**	**20,100**	2,550
	high-risk	46,100	1,060,000	1,520	31,200	**2,420**
90/70% uniform – 71·8% coverage	n/a	4,870	286,000	156	8,020	706
90/70% uniform 60% coverage	minimise R_{eff}	**26,700**	**970,000**	**1,320**	42,300	5,360
	high-risk	74,000	1,460,000	2,220	**38,500**	**3,090**
90/60% uniform – 71·8% coverage	n/a	21,700	886,000	606	21,300	1,920
90/60% uniform 60% coverage	minimise R_{eff}	**62,800**	**1,550,000**	**2,750**	59,600	7,550
	high-risk	112,000	1,880,000	3,040	**45,100**	**3,720**
80/70% uniform – 71·8% coverage	n/a	11,300	553,000	498	21,400	2,030
80/70% uniform 60% coverage	minimise R_{eff}	**43,300**	**1,250,000**	**2,520**	65,200	7,940
	high-risk	92,300	1,640,000	3,740	**59,800**	**5,400**
80/60% uniform – 71·8% coverage	n/a	38,900	1,220,000	1,510	41,500	4,040
80/60% uniform 60% coverage	minimise R_{eff}	**87,800**	**1,820,000**	**4,500**	83,000	10,100
	high-risk	136,000	2,080,000	5,000	**68,500**	**6,320**
70/50% uniform 70% coverage	minimise R_{eff}	**123,000**	**2,160,000**	**5,680**	89,200	9,760
	high-risk	133,000	2,220,000	5,830	**86,900**	**8,910**
70/50% uniform 50% coverage	minimise R_{eff}	**264,000**	**2,930,000**	14,300	145,000	16,600
	high-risk	322,000	3,050,000	**14,100**	**124,000**	**11,700**

Note: The smallest values in each scenario are bold. Maximum vaccination coverage for each age group is 90%.

Table S9: Results of vaccine scenarios with reduced effectiveness (50%) in older age groups (60+) from a two-year simulation (R_0=2·5) – daily 10 cases introduced to the community

Vaccine scenarios (e_d/e_i & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% varied 80% coverage	minimise R_{eff}	**238**	**13,600**	20	1,520	234
	high-risk	254	15,100	**18**	**1,430**	**208**
	hybrid	254	15,100	**18**	**1,430**	**208**
95/90% varied 70% coverage	minimise R_{eff}	**368**	**24,300**	**29**	**2,210**	**348**
	high-risk	1,930	119,000	107	6,130	857
	hybrid	728	51,500	47	3,350	462
95/80% varied 80% coverage	minimise R_{eff}	**360**	**24,200**	26	2,020	318
	high-risk	397	27,400	**25**	**1,890**	**282**
	hybrid	397	27,400	**25**	**1,890**	**282**
95/80% varied 70% coverage	minimise R_{eff}	**627**	**45,000**	**44**	**3,230**	**520**
	high-risk	6,330	335,000	320	15,000	2,150
	hybrid	1,530	107,000	93	6,010	866
90/80% varied 80% coverage	minimise R_{eff}	**403**	**27,400**	32	2,380	367
	high-risk	452	31,500	**31**	**2,290**	**332**
	hybrid	452	31,500	**31**	**2,290**	**332**
90/80% varied 70% coverage	minimise R_{eff}	**752**	**53,700**	**56**	**4,000**	**628**
	high-risk	8,560	422,000	473	20,700	2,890
	hybrid	1,700	116,000	111	7,060	1,020
90/70% varied 80% coverage	minimise R_{eff}	**849**	**62,200**	**58**	**4,120**	651
	high-risk	1,080	78,700	63	4,300	**638**
	hybrid	1,080	78,700	63	4,300	**638**
90/70% varied 70% coverage	minimise R_{eff}	**2,700**	**178,000**	**177**	**10,600**	**1,690**
	high-risk	25,300	901,000	1,270	40,000	5,680
	hybrid	2,910	190,000	189	11,100	1,770

Note: The model assumption is that there are daily ten cases introduced to the community. The smallest values in each scenario are bold. In all scenarios, vaccines are assumed to have half effectiveness on people aged 60 and over. The reduction of effectiveness is assumed to the same for both vaccine effectiveness on infection reduction and disease prevention.

Table S10: Two-year open border modelling results (10 imported cases/day) with means and standard deviations when the contact matrix is added with a uniform distribution (R_0=4·5)

Vaccine scenarios (e_d/e_i & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
90/80% uniform 90% coverage	minimise R_{eff}	**910±55**	**66,920±3,860**	**52.8±3.9**	**3,700 ±240**	**550±42**
	high-risk	12,070±4,260	443,070±82,106	350±120	11,500±2,040	1,030±181
	hybrid	1,440±155	102,500±9,860	69±9	4,560 ±529	600±84

Note: e_i is the vaccine effectiveness on infection reduction and e_d is the vaccine effectiveness on disease prevention. The lowest values for each scenario are in bold.

Table S11: Comparison of cases, hospitalisations and deaths in Māori and Pasifika populations (R_0=4·5) – 10 external cases introduced to the community per day

Vaccine scenarios (e_d/e_i & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform 90% coverage	minimise R_{eff}	199	10,800	19	1,480	211
	high-risk	205	11,200	16	1,290	160
	hybrid	205	11,200	16	1,290	160
95/90% uniform 80% coverage	minimise R_{eff}	539	36,200	40	2,850	435
	high-risk	1,300	64,600	54	2,890	215
	hybrid	580	38,200	31	2,170	192
95/90% uniform 70% coverage	minimise R_{eff}	5,410	177,000	331	10,300	1,550
	high-risk	14,200	237,000	556	8,960	395
95/80% uniform 90% coverage	minimise R_{eff}	461	33,300	25	1,870	228
	high-risk	502	36,100	23	1,740	193
	hybrid	502	36,100	23	1,740	193
95/80% uniform 80% coverage	minimise R_{eff}	2,770	142,000	125	6,000	778
	high-risk	4,250	161,000	135	4,950	333
95/80% uniform 70% coverage	minimise R_{eff}	17,800	365,000	832	15,500	2,170
	high-risk	25,200	380,000	830	11,600	565
90/80% uniform 90% coverage	minimise R_{eff}	636	45,800	42	3,030	350
	high-risk	700	49,500	40	2,890	308
	hybrid	700	49,500	40	2,890	308
90/80% uniform 80% coverage	minimise R_{eff}	4,610	194,000	260	10,100	1,200
	high-risk	5,940	201,000	259	8,380	668
90/80% uniform 70% coverage	minimise R_{eff}	22,300	411,000	1,290	21,700	2,840
	high-risk	28,500	418,000	1,230	17,100	1,140
90/70% uniform 90% coverage	minimise R_{eff}	7,300	285,000	296	10,400	1,090
	high-risk	7,500	287,000	277	9,580	927
90/70% uniform 80% coverage	minimise R_{eff}	22,100	470,000	903	17,300	1,700
	high-risk	22,500	467,000	811	15,300	1,270
90/70% uniform 70% coverage	minimise R_{eff}	49,100	641,000	2,350	27,700	3,630
	high-risk	51,000	634,000	1,880	21,600	1,560
80/70% uniform 90% coverage	minimise R_{eff}	20,300	457,000	1,420	28,700	3,100
	high-risk	20,500	459,000	1,360	27,200	2,800
80/70% uniform 80% coverage	minimise R_{eff}	37,700	599,000	2,470	35,600	3,640
	high-risk	37,800	597,000	2,330	33,500	3,250
80/70% uniform 70% coverage	minimise R_{eff}	65,400	729,000	4,400	45,400	5,350
	high-risk	65,400	726,000	3,850	40,000	3,630
80/60% uniform 90% coverage	minimise R_{eff}	54,900	699,000	2,960	33,900	3,670
	high-risk	55,100	700,000	2,810	32,100	3,320
80/60% uniform 80% coverage	minimise R_{eff}	73,100	791,000	3,830	37,800	3,880
	high-risk	73,700	793,000	3,660	36,000	3,520
80/60% uniform 70% coverage	minimise R_{eff}	100,000	878,000	5,650	46,000	5,530
	high-risk	99,500	876,000	4,900	40,400	3,690

Note: Vaccine coverage for each age group has no limit (100% maximum). When the herd immunity threshold is achieved, the outcomes are close to the numbers for the whole New Zealand because their magnitudes are mainly dependent on the number of daily imported cases and the R_{eff} of the simulated population. Both simulations have the same daily imported cases. The R_{eff} of these populations is slightly different from the R_{eff} of the whole NZ in the same scenario due to different age group distribution. The high-risk and hybrid strategies may have the same allocations, e.g. the first vaccine scenario. The lowest values for each scenario are in bold.

Table S12: Comparison of cases, hospitalisations and deaths in Māori and Pasifika populations (R_0=4·5) – 10 external cases introduced to the community per day. Vaccine is not allowed for children aged under 12.

Vaccine scenarios (e_d/e_i & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/90% uniform – 74% coverage	n/a	7,350	166,000	263	6,000	320
95/90% uniform 70% coverage	minimise R_{eff}	9,550	204,000	386	8,150	551
	high-risk	11,500	224,000	422	8,080	380
95/90% uniform 60% coverage	minimise R_{eff}	25,500	373,000	1,420	19,600	2,670
	high-risk	39,100	406,000	1,480	14,800	585
95/80% uniform – 74% coverage	n/a	13,700	283,000	423	8,300	464
95/80% uniform 70% coverage	minimise R_{eff}	18,900	353,000	668	11,600	813
	high-risk	21,100	363,000	670	10,800	547
95/80% uniform 60% coverage	minimise R_{eff}	44,600	548,000	2,170	24,400	3,590
	high-risk	53,100	546,000	1,770	17,100	754
95/80% uniform – 74% coverage	n/a	16,200	322,000	679	12,800	935
95/80% uniform 70% coverage	minimise R_{eff}	22,400	396,000	1,050	17,400	1,500
	high-risk	24,400	402,000	1,030	16,100	1,110
95/80% uniform 60% coverage	minimise R_{eff}	49,900	584,000	2,890	31,500	4,310
	high-risk	56,700	578,000	2,390	23,600	1,490
95/80% uniform – 74% coverage	n/a	35,600	561,000	1,280	18,400	1,440
95/80% uniform 70% coverage	minimise R_{eff}	45,700	625,000	1,910	23,700	2,350
	high-risk	46,700	626,000	1,700	20,900	1,540
95/80% uniform 60% coverage	minimise R_{eff}	78,400	765,000	3,910	35,200	4,840
	high-risk	79,800	754,000	2,960	26,500	1,770
95/80% uniform – 74% coverage	n/a	50,600	670,000	3,020	36,800	3,470
95/80% uniform 70% coverage	minimise R_{eff}	61,000	720,000	3,810	41,700	4,180
	high-risk	61,800	722,000	3,620	39,400	3,610
95/80% uniform 60% coverage	minimise R_{eff}	93,500	828,000	6,220	52,300	6,430
	high-risk	92,900	824,000	5,220	44,800	3,920
95/80% uniform – 74% coverage	n/a	86,000	841,000	4,220	38,200	3,620
95/80% uniform 70% coverage	minimise R_{eff}	96,000	875,000	5,020	42,600	4,350
	high-risk	96,600	875,000	4,710	40,000	3,680
95/80% uniform 60% coverage	minimise R_{eff}	126,000	945,000	7,210	51,400	6,410
	high-risk	124,000	941,000	6,020	44,000	3,840

Note: Vaccine coverage for each age group has no limit (100% maximum). Maximum attainable vaccine coverage is 74%.

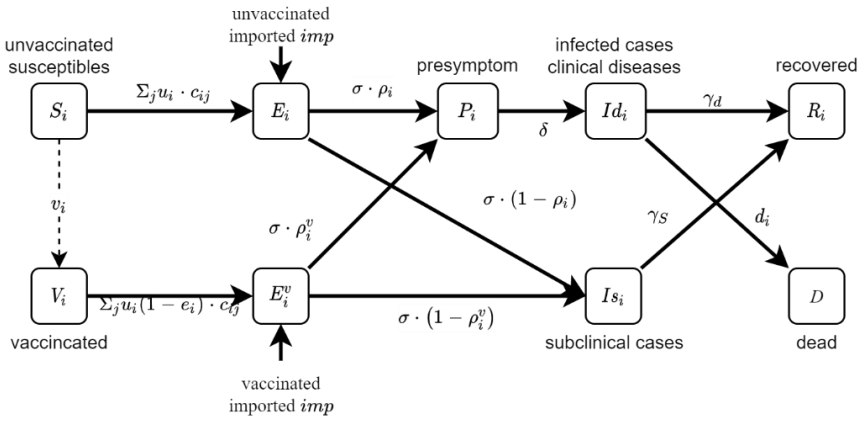


Figure S1: The age-stratified SEIR model for COVID-19.

Note: The transition parameters δ, γ_d, γ_S, σ are the inverse of the average periods in the corresponding former compartments. Specifically, $\sigma=1/3{\cdot}8$ with $3{\cdot}8$ days as the latent period, $\delta=1/t_p$ with t_p as the average presymtomatic infectious period, $\gamma_d = (1-d_i)/t_d$ and $\gamma_S=1/t_S$ with t_d and t_s as the average infectious periods of clinical and subclinical cases respectively (Supplemental Table S1), d_i is the death rate of age group i. Refer to Method section for the description of compartments and other parameters.

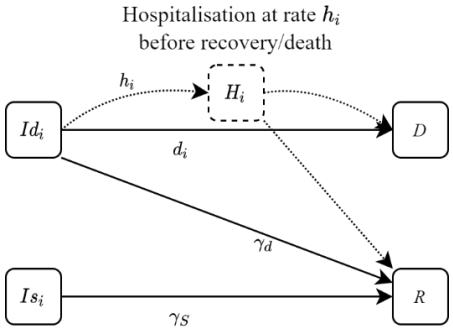


Figure S2: Modelling hospitalisations.

Note: d_i and h_i is the death rate and hospitalisation rate of age group i.

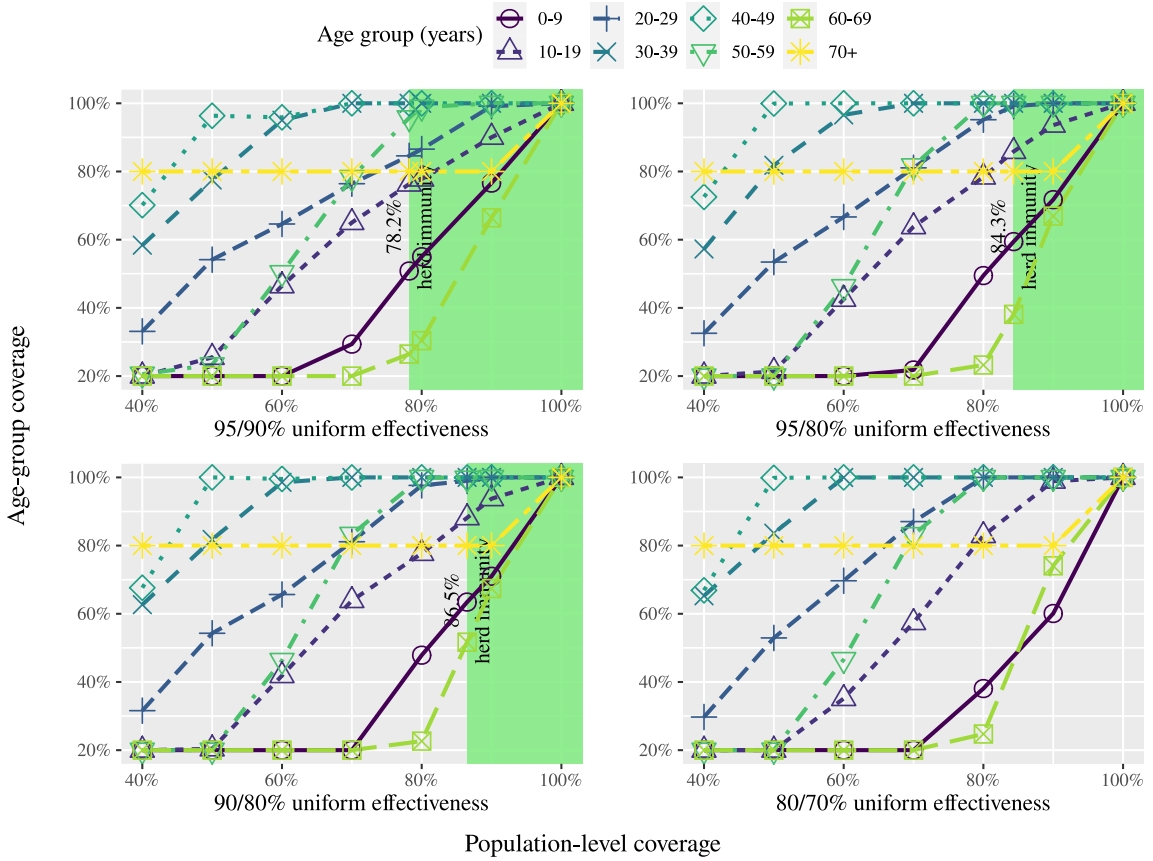


Figure S3: Age-group allocations of vaccine strategy 1 at various VE scenarios (R_0=4·5)

Note: Vaccine allocations of the spread-minimising strategy (strategy 1) at fixed uptake levels and minimal uptake level required for the herd immunity threshold (border lines of the green areas). A vaccine has two values of effectiveness: disease prevention and infection reduction. The effectiveness of a vaccine is called “uniform” if their effectiveness is equal across age groups.

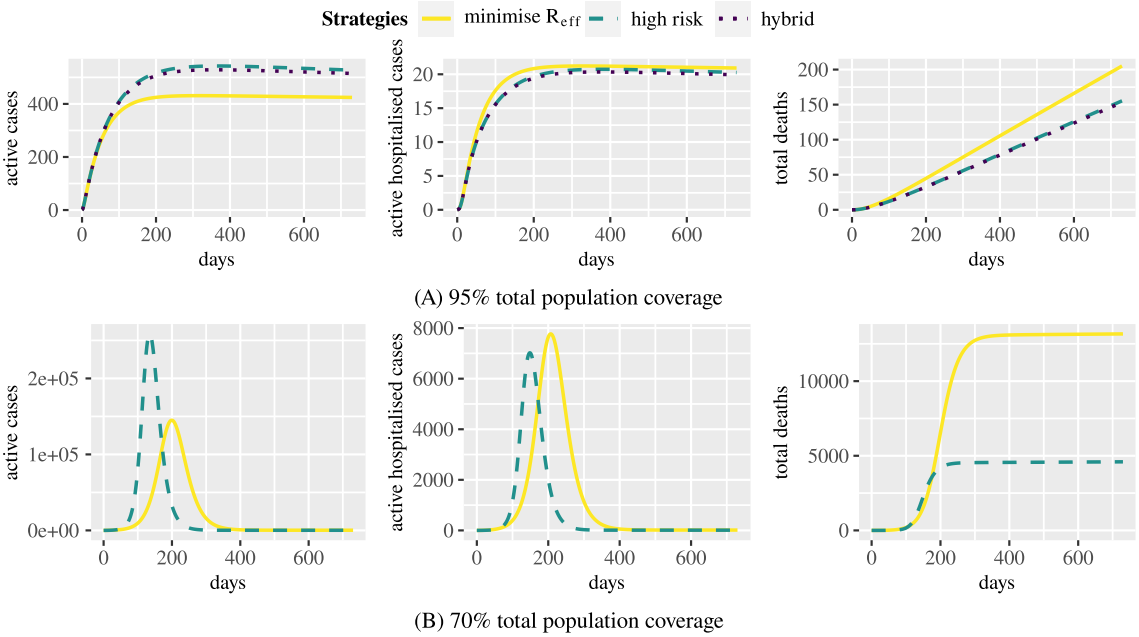
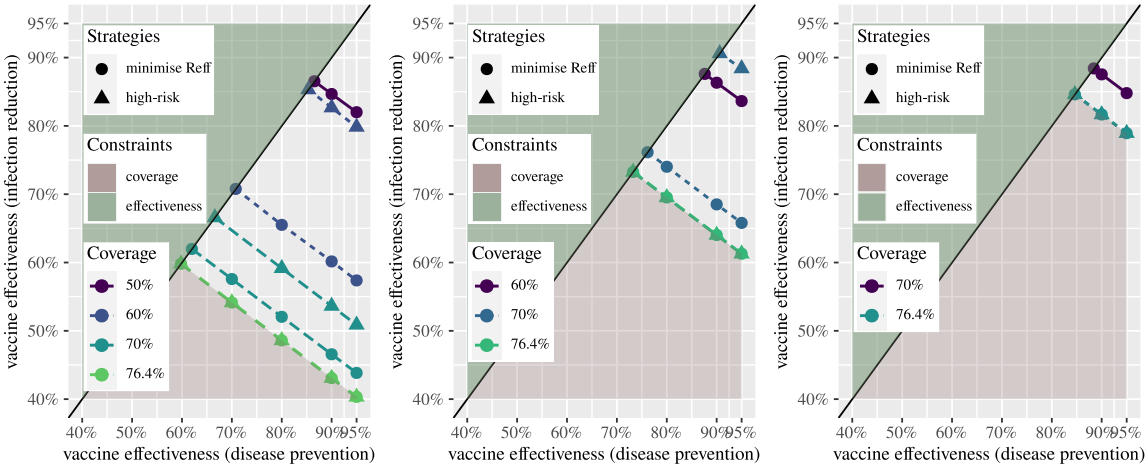


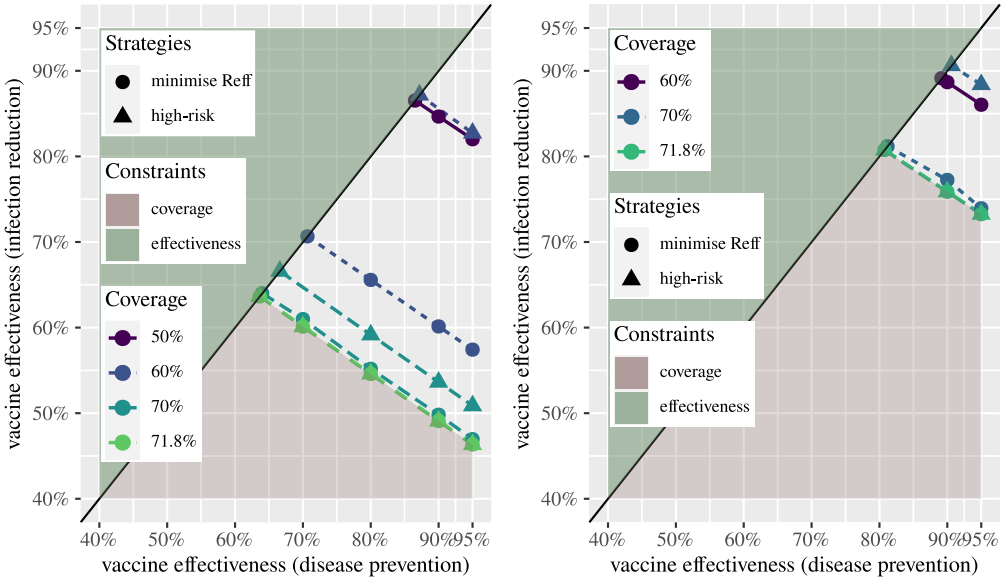
Figure S4: The changes of active cases and hospitalised cases over the two-year period of simulations (R_0=4·5) – 90/80% uniform effectiveness with (A) 95% coverage – and (B) 70% coverage



(A) Varying coverage - $R_0 = 2$ (B) Varying coverage - $R_0 = 2.5$ (C) Varying coverage - $R_0 = 3$

Figure S5: Vaccine effectiveness and New Zealand population vaccine uptake requirements for the herd immunity threshold (R_0=2–3·5) with vaccination allowed for individuals aged at least 12

Note: The minimal VE of infection reduction and disease prevention for the herd immunity threshold at multiple vaccine uptake levels given a fixed R_0=2 (A), 2·5 (B), and 3 (C). Vaccine coverage for each age group is limited to 90% maximum. HIT is not achievable for R_0=3·5 in this scenario.



(A) Varying coverage - $R_0 = 2$ (B) Varying coverage - $R_0 = 2.5$

Figure S6: Vaccine effectiveness and New Zealand population vaccine uptake requirements for the herd immunity threshold (R_0=2–3·5) with vaccination allowed for individuals aged at least 16

Note: The minimal VE of infection reduction and disease prevention for the herd immunity threshold at multiple vaccine uptake levels given a fixed R_0=2 (A) and 2·5 (B). Vaccine coverage for each age group is limited to 90% maximum. HIT is not achievable for R_0=3 and 3·5 in this scenario.

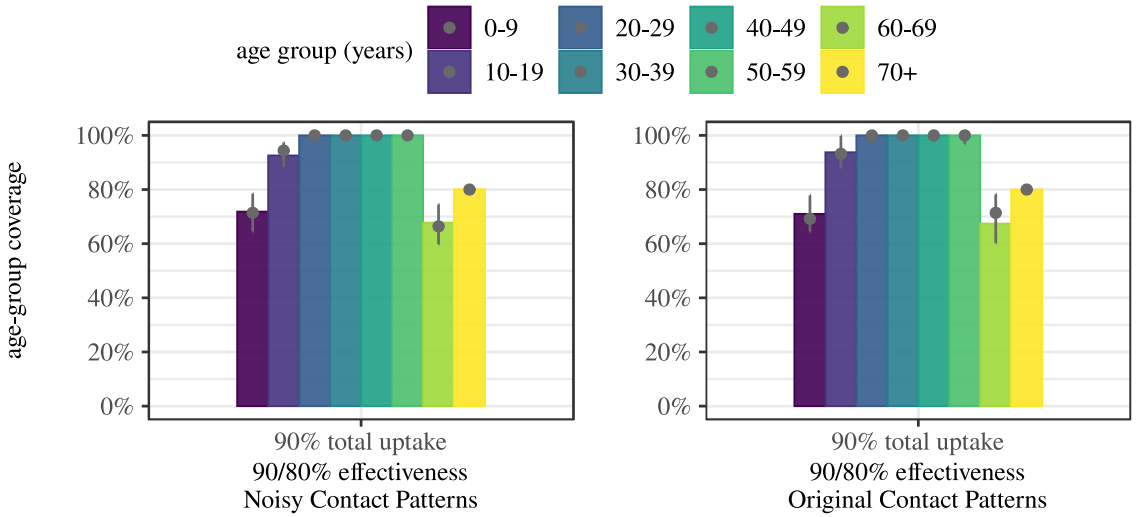
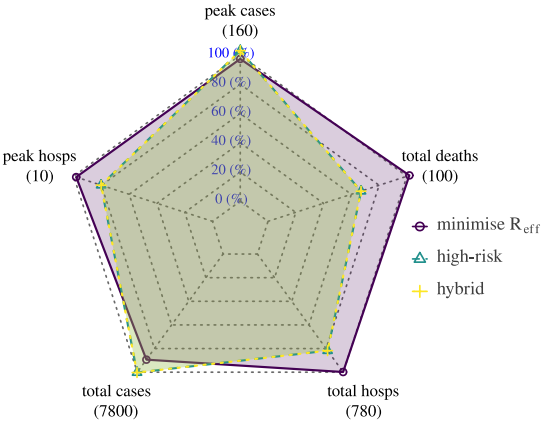
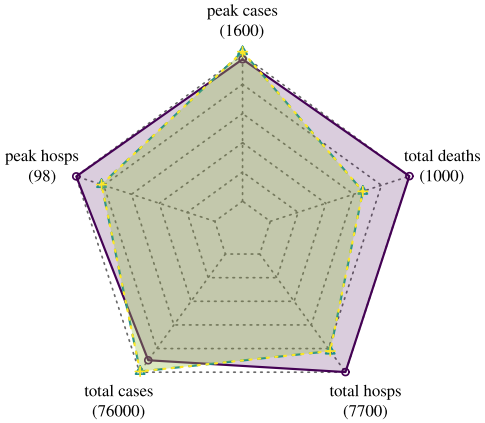


Figure S7: Comparison of the changes of vaccine allocations (using the spread-minimising strategy) caused by slightly changing the contact matrix and by 50 times of optimising R_{eff} with the original contact matrix (and different random seeds).

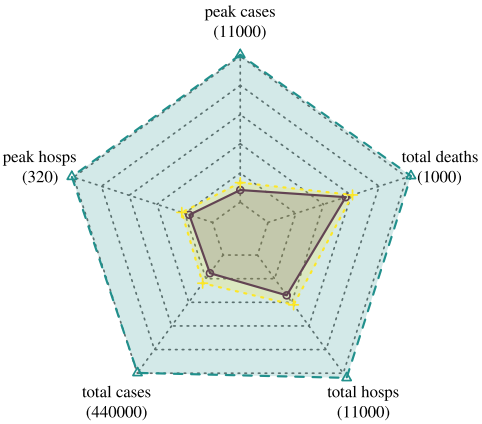
Note: The variations of vaccine allocations caused by adding noise to the contact matrix are generally smaller than the deviations caused by different random seeds. 90/80% effectiveness means the vaccine has 90% effectiveness on preventing disease and 80% effectiveness on reducing infection. Vaccine effectiveness here is considered equal across age groups.



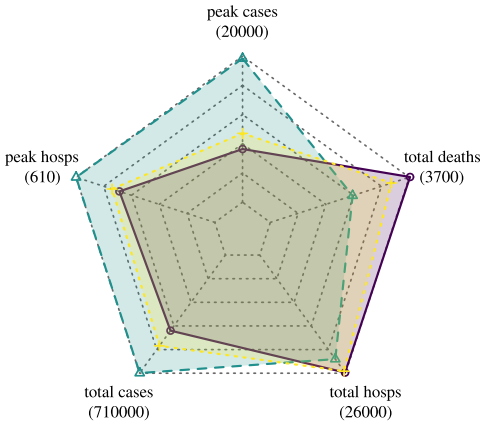
(A) 95/90% effectiveness - 95% coverage - import 10 cases/day



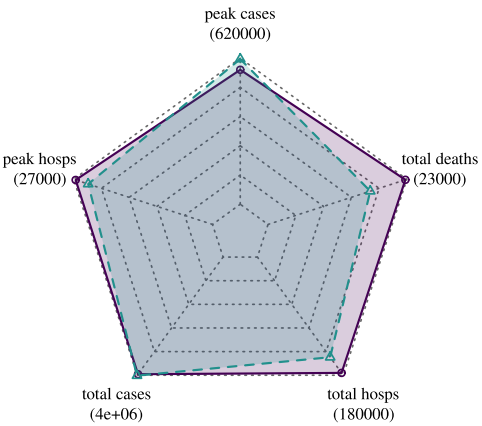
(B) 95/90% effectiveness - 95% coverage - import 100 cases/day



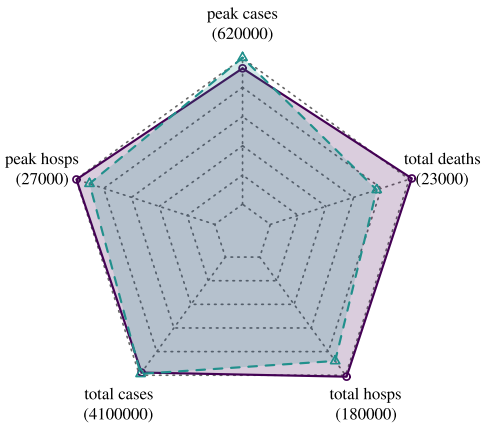
(C) 90/80% effectiveness - 90% coverage - import 10 cases/day



(D) 90/80% effectiveness - 90% coverage - import 100 cases/day



(E) 70/50% effectiveness - 80% coverage- import 10 cases/day



(F) 70/50% effectiveness - 80% coverage- import 100 cases/day

Figure S8: Varying daily number of imported cases – the changes of outcome rankings among vaccine strategies (spread-minimising, high-risk, and hybrid strategies) (R_0=4·5)

Note: Forecasts for a two-year simulation with three vaccine strategies under three vaccine scenarios with varying daily number of imported cases that blend into community. The hybrid vaccine strategy is not available in the last two scenarios as the total uptake is not enough for the herd immunity threshold. The "total cases" measure only counts community cases, which excludes 7,300 imported cases for 10 imported cases/day or 73,000 imported cases for 100 imported cases/day.

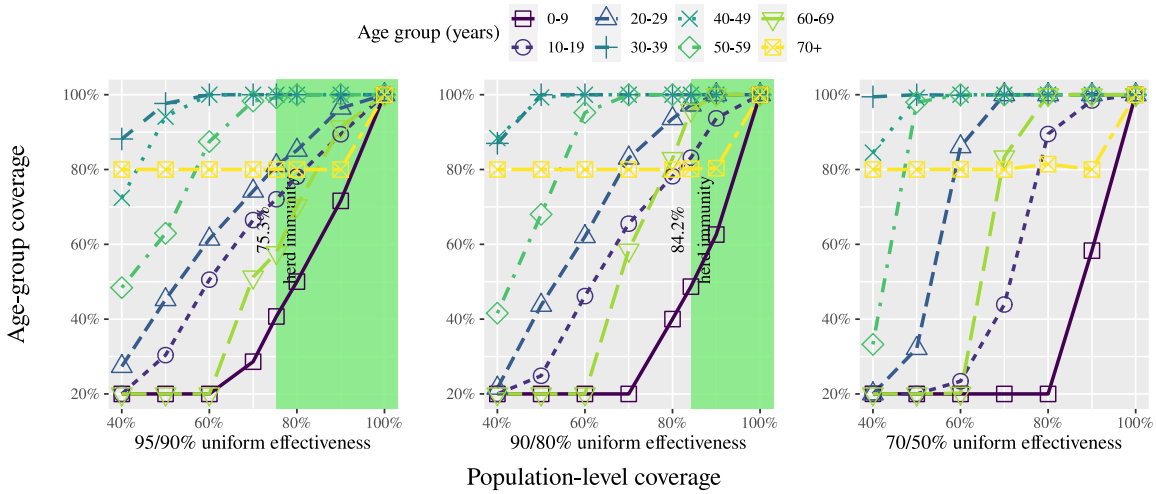


Figure S9: Vaccine allocations of the spread-minimising strategy and minimal herd-immunity uptake levels customised for the combined Māori and Pasifika populations

Appendix S1 – The age-stratified SEIR model

We used an age-stratified SEIR model with a presymptomatic infectious phase. Supplemental Figure S1 illustrates the age-stratified extended SEIR model for one age group *i*. Compartment E_i corresponds to exposed individuals, E_i^v to exposed vaccinated individuals, P_i to presymptomatic infectious cases, Id_i to post-symptomatic clinical cases, Is_i to asymptomatic/paucisymptomatic (subclinical) infected cases, and R_i to recovered individuals of age group *i*. Compartment *D* includes all deaths from COVID-19. P_i and Id_i are associated with "clinical cases" that will develop (P_i) or have developed (Id_i) clinically-detectable features of disease, i.e. moderate to severe symptoms. Is_i includes subclinical cases that are either asymptomatic or paucisymptomatic. The susceptible compartment (S_i) includes people of age group *i* without vaccination. The vaccinated compartment (V_i) refers to vaccinated people in age group *i*. Parameters used in this model are listed in Supplemental Table S1.

The Next Generation Matrix

Based on the contact matrix of New Zealand (NZ)[17,18] where each individual of age group *i* makes contact with c_{ij} individuals of age group *j*, we derived the force of infection for an individual in age group *i* is:

$$\lambda_i = U_i \sum_j c_{ij}(P_j + Id_j + fIs_j)/N_j \quad (1)$$

where U_i is the susceptibility of an age group *i*, Id_j, Is_j and P_j are the clinically symptomatic, subclinical and presymptomatic cases in age group *j* respectively. N_j is the population size of age group *j*. Therefore, $(P_j + Id_j + fIs_j)/N_j$ is equivalent to the probability of encountering an infectious case per contact.

An entry at row *i* and column *j* of the next generation matrix (NGM) of unvaccinated population for the basic reproduction number R_0 considering infected cases for each age group is as follows:

$$NGM_{ij}^0 = U_0 \frac{u_i N_i c_{ij}}{N_j}\left(\rho_j(t_P + t_d) + f\left(1-\rho_j\right)t_S\right), \quad (2)$$

where $t_P = 1/\delta$, $t_d = 1/\gamma_d$ are presymptomatic and symptomatic infectious periods for clinical infections; $t_s = 1/\gamma_s$ is the infectious period of subclinical cases; f is an assumed reduction of infectiousness in subclinical cases compared with clinical ones; N_j is the population size of an age group *j*; ρ_j is the relative clinical fraction for age group *j*; and U_0 and u_i are respectively the susceptibility scaling factor and relative susceptibility of age group *i* so the absolute susceptibility of the age group *i* is $U_i = U_0 u_i$. The initial value of susceptible group S_i is N_i, which is the population of age group *i*. The leading eigen value of the NGM^0 is the basic reproduction number R_0.

By calculating the unscaled NGM (without U_0), where each entry is $unscaled\_NGM_{ij}^0 = NGM_{ij}^0/U_0$, we can infer the value of U_0 given an assumed R_0 value (assumed R_0=2·5) as:

$$U_0 = R_0/lead\_eigen(unscaled\_NGM^0), \quad (3)$$

where $lead\_eigen(unscaled\_NGM^0)$ is the leading eigen value of the unscaled NGM. For effective reproduction number (R_{eff}), an element of the initial NGM can be simplified as follows:

$$NGM_{ij}^v = \frac{U_0 u_i (N_i - V_i e_i) c_{ij}}{N_j}\left(\rho_j'(t_P + t_d) + f\left(1-\rho_j'\right)t_S\right), \quad (4)$$

where V_i is the vaccinated compartment of age group *i* and $\rho_j' = \rho_j \frac{N_i - V_i e_d}{N_i - V_i e_i}$ is the transformed clinical rate for both vaccinated and unvaccinated cases.

The simulation of different vaccine strategies can evaluate the outcomes of the vaccine allocations without other effects, such as the reinforcement of the vaccination process and the waning vaccine effect. This enables analyses of how the distribution of immunisation influences the outcomes on the medical system and total deaths. The transition from infections with clinical disease (Id_i) to recovery and deaths is elaborated into an intermediate compartment H_i (Supplemental Figure S2), which includes the hospitalised cases of age group *i*.

All these values to be minimised in vaccine strategies are initial values and are expected to be reduced as a result of increasing immunity due to viral spread among the community and the continuous vaccination process.

Appendix S2 – Comparison of vaccination strategies

This supplementary material provides the forecasted outcomes from two-year simulations of vaccination strategies investigated in the study, which include: (1) the spread-minimising strategy that minimises R_{eff}; (2) the high-risk

targeting strategy that prioritises the oldest population, i.e. the population with the highest risk for COVID-19 disease and deaths; and (3) the hybrid strategy that minimises R_{eff} to achieve the herd immunity threshold (HIT) ($R_{eff} \leq 1$, if possible) using the least vaccine coverage and prioritises the rest of the vaccine uptake on the oldest population. The third strategy is only available when the first strategy can achieve HIT. Supplemental Figure S3 illustrates the results of vaccine distributions by the spread-minimising strategy (strategy 1).

The standard approach to vaccination in areas of active disease transmission is to prioritise groups of high-risk of poor outcomes, such as older age groups.[19] When implementing a herd-immunity strategy, it is also important to eliminate the virus as quickly as practicable. Thus, a third vaccine strategy, called 'hybrid strategy', is to reduce R_{eff} to 1 before prioritising the high-risk population. This strategy aims to balance between two potential risks: the spreading rate if SARS-CoV-2 is introduced before completing the vaccination process and the total COVID-19-related deaths and hospitalisations.

In the open border simulation, the number of total imported cases (that blend into the community) is 7,300 cases. With a fixed age distribution of the past arrived cases,[14] the predicted hospitalised and death cases from the 7,300 imported cases are constant across all scenarios and vaccine strategies. The total number of hospitalised cases is:

$$H_{total} = \sum_i imports_i * hosp\_rate_i * 7300,$$

and the total number of death cases is:

$$D_{total} = \sum_i imports_i * death\_rate_i * 7300,$$

where $imports_i$ is the number of daily imported cases that fall in the age group i, $hosp\_rate_i$ and $death\_rate_i$ are the hospitalisation and death rate of the age group i respectively. We assumed all imported cases are unvaccinated before infections. Thus, their age-stratified death rates and hospitalisation follow the age-stratified death rates modelled by Verity et al.[12] and the age-stratified hospitalisation rates from Episurv[14] respectively. For the course of two years (730 days), the expected total hospitalisations of imported cases are 444 cases and the expected total deaths of imported cases are 49·6 cases.

The forecasted results of infected cases, hospitalised cases, and death cases of three vaccine strategies in various vaccine scenarios and R_0 values are shown in Supplemental Tables S2–9. Supplemental Table S2 includes the scenarios of R_0=4·5 and vaccines with uniform effectiveness across age groups where vaccine is allowed for people aged over 16. This table complements Table 1 and 2 in the main text that show the modelling results of the same R_0 value but vaccination is allowed for different age groups. Similarly, Supplemental Tables S3–5 contain the modelling results of the same vaccine scenarios but a lower R_0 value of 6, while Tables S6-8 are for the R_0 value of 2·5. Supplemental Table S9 shows the modelling results of vaccines with immune senescence. Results are rounded to the third significant number or rounded to integers if smaller than 100. Although there is high coverage with 95% vaccine effectiveness, the number of cases might be still high. However, the percentages of hospitalised cases have been reduced. Supplemental Figure S4 shows the changes of active cases and hospitalisations over the simulation period when the vaccine scenario is 95/70% uniform effectiveness and 80% coverage for total uptake. Since there are continuous introductions of oversea cases, these measures are not reduced to (near) 0(s) after reaching their peaks.

Appendix S3 – Minimal herd immunity requirements for different R_0 values, vaccine effectiveness, and vaccination strategies

This section provides the additional analyses of HIT requirements regarding vaccine effectiveness in many scenarios of different R_0 values, vaccination age restriction, and vaccine strategies. The analyses of HIT requirements where vaccination is allowed for all age groups are available in the main text. Where R_0 is in the range of [2, 3·5], maximum vaccine coverage for each age is assumed to be 90%. With higher R_0 values (>4), we enabled the maximum vaccine coverage to as much as 100% (no limit). HIT is not achievable for higher R_0 values when vaccination is restricted to the 12 or 16 year-and-older. Figure S5-6 show the HIT requirements for lower R_0 values (no greater than 3·5). Without vaccinating the children aged under 12, HIT is not achievable for R_0=3·5.

Appendix S4 – Sensitivity Analysis

The limitation of this study was that the contact matrix were obtained through synthesising based on population demographics and residential statistics in.[17] Contact patterns are also subject to variation at different time of the year. To address this limitation, we analysed the changes in vaccine allocations and modelling results by adding a random value to each element c_{ij} of the contact matrix. The added random value for each c_{ij} was generated by a uniform distribution with the mean of 0 and the boundaries of $(-10\%c_{ij}, 10\%c_{ij})$. We generated 50 new contact matrices using this method. Supplemental Figure S7 provides the vaccine allocations of corresponding vaccine

scenarios with the original (on the right) and a noise-added contact matrix (on the left). The variations of vaccine allocations of the spread-minimising strategy were smaller than the variations by different random seeds. The two-year modelling results of 50 different noise-added contact matrices had small standard deviations compared with mean values (Supplemental Table S9).

Higher numbers of imported cases will normally result in higher numbers of infections, hospitalisations, and deaths. This was confirmed by varying the number imported cases and observing the outcomes in different scenarios (Supplemental Figure S8). The pairs of Figures S8A vs. S8B, S8C vs. S8D, and S8E vs. S8F show the same scenario with different numbers of daily imported cases. The rankings of strategies in terms of cases and peak hospitalisations remained unchanged when the number of daily imported cases increases. However, the total hospitalisations and deaths of the high-risk targeting strategy was the lowest among three strategies in the cases where the uptake was low and the vaccine effectiveness (VE) of infection reduction was high, e.g. 90/80% effectiveness and 90% coverage (Figures S8C and S8D). This is due to, under the high-risk targeting strategy, HIT being achieved faster through a higher number of imported cases. It is noted that the higher peak of hospitalisations of the high-risk targeting strategy (324), which is near the hospitalisation capacity,[20] could result in additional deaths from non-COVID-19 causes that are not able to receive appropriate and timely treatment. Only in the scenario of 70/50% effectiveness and 80% coverage in Figures S8E and S8F, where the R_{eff} value is much higher than 1 (no HIT), the outcomes between two different numbers of imported cases are similar. This is because, when $R_{eff} >> 1$, the total number of imported cases is very small compared with the outbreak size.

Appendix S5 – Modelling Māori and Pasifika populations

This section provides modelling results for Māori and Pasifika populations using the age-group distribution of their combined populations. The vaccine allocations of the high-risk targeting strategy priorities maximum coverage for the oldest age groups before allocating younger groups. For Māori and Pasifika populations, this strategy can cover up to younger groups compared with its coverage for the whole NZ when the proportions of total vaccinated population are the same. This is due to that Māori and Pasifika populations have a much lower population distribution on old age groups. Supplemental Figure S9 illustrates the vaccine allocations of the spread-minimising strategy for the combined Māori and Pasifika populations. The age-group prioritisation of the spread-minimising strategy in these populations is analogous to overall NZ population with 30–49 year olds to be prioritised. However, the strategy of minimising R_{eff} for the Māori and Pasifika populations allocates more vaccinations to the older age group (50–69 year olds) compared with the same strategy for the whole NZ. The minimal uptake for HIT is also lower in these populations. A possible reason is that the Māori and Pasifika populations are relatively young populations[9] with a larger proportion of the population in the youngest age group (0–9 years old), which does not contribute as much to viral spread. This age group has the lowest susceptibility to the virus and does not have as many contacts compared with other groups (e.g. 30–49 years).

Two-year simulations of various scenarios were run for these populations where the transmission from other ethnic groups was considered as imported cases. These results as shown in Supplemental Table S11-12 have similar trends as described for whole NZ population but with smaller scales of all investigated measures. The differences among the measures of the vaccine strategies, especially at 80% coverage, are much smaller. The reason is that, with 80% coverage, the vaccine distributions only differ substantially in the age group 0–9 (with the largest population), which does not contribute much to both viral spread, hospitalisations, and deaths.

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From: Bryan Chapple [TSY]
To: Vince Galvin
Cc: Pubudu Senanayake; Christopher Nees [TSY]; George Whitworth [DPMC]
Subject: RE: Confirmed agenda and papers: Covid-19 Modelling Governance Group
Date: Wednesday, 14 July 2021 5:39:10 PM
Attachments: image001.png

Hello Vince,

Thanks for following up with your thoughtful email. I don't know enough to know how much these issues have been considered by the steering group, so have copied in Chris and George to get their take.

I'm on leave now for a bit, so can follow up on my return.

Cheers
Bryan

From: Vince Galvin <xxxxx.xxxxxx@xxxxx.xxxx.xx>
Sent: Wednesday, 14 July 2021 4:07 pm
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>
Cc: Pubudu Senanayake <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>
Subject: FW: Confirmed agenda and papers: Covid-19 Modelling Governance Group

Hey Bryan

With all that we had to get through yesterday it didn't feel like the right time to talk about some drier topics;

You made a very fundamental point yesterday about the danger of people thinking there is more knowledge in these modelling results than there really is. This seemed to be a much more substantial concern than that sort of meeting had the time to address. I do think it is worth teasing out this a bit more as it is easy to convey the PM's interest in having options around what NCIs might sit around an achievable vaccine response rate but this involves being prepared to identify both packages of interventions and assumptions about the interventions effectiveness so it will quickly get into the layers of scenarios that you expressed concerns about.

I know we will ensure that we will make assumptions transparent and so forth but this has the feeling to me of a situation where all the roles and responsibilities need to be clear. I understand from Pubudu that the group has been doing some thinking about this so maybe it worth hearing from them;

I'm wary of covering points that they have worked through but a few things I am interested in understanding better are;

- How is the development of the scenarios going to be signed off. The temptation is to get a small group in a room and invent a range of options. This is fine if the purpose of the activity is to illustrate the interaction between the range of realistic values for input assumptions and key outcomes but if we are talking about policy options I think it would be better to have some approval structure around the options given to the modellers.

- Does someone have the role of taking all the TPM (and other agency modelling) output and accumulating it into a coherent body of knowledge that is available to other agencies. I know TPM publish everything but I feel there is a role of ownership of the accumulated work. If this is already well in hand then that's great but to me TPM is a contracted technical advice giver and there are a whole lot of roles about owning the frameworks we are working in, keeping track of what has actually been asked for, managing knowledge, extracting insight, giving advice and identifying what needs to be communicated to other agencies as standard operating assumptions, etc. It looks like plenty of this work of this type is being done but I think it would be good to understand what structure has been put around this sort of work.

- What is the relationship of this policy work to the agencies that have to do the implementation ? It seems like some of the modelling work done by TPM (and now maybe Richard Arnold) would be the basis of an operational risk management framework that could be continuously updated and refined to help agencies manage their efforts in managing MIQ facilities, operations at the border, crisis management or whatever operational functions are necessary. I am not clear if these sorts of operational risk management frameworks are in place and how they make use of the modelling work that has been done (or this is something that is outside our scope).

Please feel free to ignore this if it is well covered ground that I have not caught up with. I'm not normally a "process" person but one of the possible responses to your excellent question is to use frameworks for being clear about what issues have been considered and not considered and how this was all governed.

Cheers

Vince

From: Christopher Nees [TSY] <xxxxx.xxxx@xxxxxxxx.xxxx.xx>
Sent: Friday, 9 July 2021 4:48 PM
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MBIE: Paul Stocks <xxxx.xxxxxx@xxxx.xxxx.xx>; ^MSD: Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; Vince Galvin <xxxxx.xxxxxx@xxxxx.xxxx.xx>; Ian Town <xxx.xxxx@xxxxxx.xxxx.xx>; pmcsa <xxxxx@xxxxxxxx.xx.xx>; ^EXT: Talosaga Talosaga <xxxxxxxx.xxxxxxxx@xxxxxx.xxxx.xx>
Cc: Rebecca Mountfort [TSY] <xxxxxxx.xxxxxxxxx@xxxxxxxx.xxxx.xx>; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; xxxxxxxx.xxxxxxxx@xxx.xxxx.xx; Gill Hall <xxxx.xxxx@xxxxxx.xxxx.xx>; Pubudu verSenanayake <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>; Patricia Priest <xxxxxxxx.xxxxxx@xxxxxx.xxxx.xx>; Ryan Walsh [TSY] <xxxx.xxxxx@xxxxxxxx.xxxx.xx>
Subject: Confirmed agenda and papers: Covid-19 Modelling Governance Group

Kia ora koutou Modelling Governance Group

Please find attached the confirmed agenda and papers for Tuesday's modelling governance group meeting.

Ngā mihi

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-
I do not work on Thursdays.

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From: Ryan Walsh [TSY] <xxxx.xxxxx@xxxxxxxx.xxxx.xx>
Sent: Monday, 5 July 2021 3:19 PM
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MBIE: Paul Stocks <xxxx.xxxxxx@xxxx.xxxx.xx>; ^MSD: Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; xxxxx.xxxxxx@xxxxx.xxxx.xx; Ian Town <xxx.xxxx@xxxxxx.xxxx.xx>; pmcsa <xxxxx@xxxxxxxx.xx.xx>; xxxx.xxxx@xxxxxx.xxxx.xx; xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx; xxxx.xxxxxxxx@xxx.xxxx.xx
Cc: Christopher Nees [TSY] <xxxxx.xxxx@xxxxxxxx.xxxx.xx>; Sam Tendeter [TSY] <xxx.xxxxxxxx@xxxxxxxx.xxxx.xx>; Bevan Lye [TSY] <xxxxx.xxx@xxxxxxxx.xxxx.xx>; Rebecca Mountfort [TSY] <xxxxxxx.xxxxxxxxx@xxxxxxxx.xxxx.xx>; xxxxxxxx.xxxxxx@xxxxxx.xxxx.xx; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; xxxxx.xxxx@xxxx.xxxx.xx; xxxxxxxx.xxxxxxxx@xxx.xxxx.xx
Subject: Agenda: Covid-19 Modelling Governance Group

[IN-CONFIDENCE]

Good afternoon All,

For next week's Governance Group meeting we were proposing the following items for the agenda:

1. General updates/context
2. Summary of TPM 'frequency of large outbreaks' paper
3. Proposed priorities for the modelling program

Papers for items 2 and 3 will be circulated later this week.

Please let me know if there are any other items that you would like added.

Very happy to discuss and looking forward to next week's meeting,

Ryan

From:	Christopher Nees [TSY]
To:	Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; xxxxx.xxxxxx@xxxxx.xxxx.xx; Ian Town; pmcsa; ^EXT: Talosaga Talosaga
Cc:	Rebecca Mountfort [TSY]; George Whitworth [DPMC]; xxxxxxxx.xxxxxxxx@xxx.xxxx.xx ; Gill Hall; xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx ; Patricia Priest; Ryan Walsh [TSY]
Subject:	Confirmed agenda and papers: Covid-19 Modelling Governance Group
Date:	Friday, 9 July 2021 4:47:00 PM
Attachments:	4482665 Agenda - COVID Modelling Governance Group meeting 13 July.DOCX v0.2 Frequency of Serious Outbreaks.docx 4473361 Next steps for modelling - input.DOCX image003.png

Kia ora koutou Modelling Governance Group

Please find attached the confirmed agenda and papers for Tuesday's modelling governance group meeting.

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-
I do not work on Thursdays.

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From: Ryan Walsh [TSY] <xxxx.xxxxx@xxxxxxxx.xxxx.xx>
Sent: Monday, 5 July 2021 3:19 PM
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MBIE: Paul Stocks <xxxx.xxxxxx@xxxx.xxxx.xx>; ^MSD: Nic Blakeley <xxx.xxxxxxxxxxx@xxx.xxxx.nz>; Cheryl Barnes [DPMC] <xxxxxx.xxxxxx@xxxx.xxxx.xx>; xxxxx.xxxxxx@xxxxx.xxxx.xx; Ian Town <xxx.xxxx@xxxxxx.xxxx.xx>; pmcsa <xxxxx@xxxxxxxx.xx.xx>; Gill.Hall@health.govt.nz; xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx; xxxx.xxxxxxxx@xxx.xxxx.xx
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Subject: Agenda: Covid-19 Modelling Governance Group

[IN-CONFIDENCE]

Good afternoon All,

For next week's Governance Group meeting we were proposing the following items for the agenda:

1. General updates/context
2. Summary of TPM 'frequency of large outbreaks' paper
3. Proposed priorities for the modelling program

Papers for items 2 and 3 will be circulated later this week.

Please let me know if there are any other items that you would like added.

Very happy to discuss and looking forward to next week's meeting,

Ryan

Agenda: COVID-19 Modelling Governance Group 13 July 2021

Chair: Bryan Chapple, Deputy Secretary, Macroeconomics and Growth, **The Treasury**

Members: **DPMC**: Cheryl Barnes, **MOH**: Ian Town, Talo Talosaga **MBIE:** Paul Stocks, **StatsNZ:** Vince Galvin **MSD:** Nic Blakeley, **PMCSA**: Juliet Gerrard.

1. **Welcome and apologies** (apologies from Nic)
2. **General updates/context (all)**

   Purpose: To share information on recent developments. Possible items include:

   - Progress on 'reconnecting New Zealand' work program; and
   - Views on coverage of the release of TPM's first vaccine modelling paper and how that may inform broader communications on reopening.

3. **Update and summary of TPM's 'frequency of large outbreaks' paper (George W/Chris N)**

   Purpose: to discuss the key results of the next step in TPMs modelling work and seek feedback on proposed further work to support August Cabinet report-backs.

   Context: The Steering Group have been engaging with TPM on the 'frequency of large outbreaks' paper as their next key output following the report released in early-July. Outputs of this paper will inform key parts of the report back to Cabinet in August on the reconnecting New Zealand strategy.

   Key themes: The paper models the expected frequency of "serious outbreaks" under varying international arrival rates and characteristics of who arrives into the country. The paper looks at the implications of different border policies on the these outbreaks, such as requiring arrivals to be vaccinated, self-isolate, or take a test on arrival.

   TPM's latest modelling outcomes align with their earlier findings to the extent that, until we have a large proportion of the population vaccinated, we are likely to see frequent incursions that lead to large outbreaks (absent a public health response). Key messages include:

   - To maintain 'risk' at something close to a 'status quo' rate we would need to keep arrival levels low, have relatively stringent border controls, and vaccinate a large percentage of the population.
     - Noting that the health impacts of those outbreaks will significantly drop as vaccination increases, which means that using the status quo as measure of risk becomes less useful over time.
   - Vaccination helps us get 'low prevalence' countries to 'manageable' risk levels but cannot achieve this for 'high prevalence' countries.
   - The model tells us how often we'd have to 'react' but what that reaction could look like will differ each time. For example, early in the vaccination programme it's more likely we'd need to respond with alert level measures, whereas later in the roll out we would have more time to allow measures like contact tracing etc to respond.
   - Over time most infections will come from vaccinated people. This has significant implications for how we should think about surveillance measures and ensuring people realise their ongoing level of risk. Like the previous work, it implies a need for enduring public health protocols to manage COVID-19 risks even post-vaccine rollout.

   We seek feedback on what we are asking TPM to do from here to support the August process:

- Model other post-border controls on outbreaks (different strategies to detect cases pre-outbreak), for example where:
  - vaccinated arrivals only isolate until they have the results from their arrival test? (e.g. 3 days)
  - no isolation for vaccinated travellers, but a test at 7-days post arrival?
  - Impact of not requiring symptomatic people (who are not contacts of a known case) to isolate until their test is returned,
  - Use of lower sensitivity tests (used at a more frequent rate)
- Run some sensitivity analysis in the large outbreak model to understand:
  - the full distribution of outbreaks in the model, e.g outbreaks of 2-19, 20-49, 50-99 and 100+?
  - How many generations/how long does it take for the 'large outbreak' threshold to be met? (e.g. a few days, a week etc).
  - How often we 'lose control' of an outbreak (e.g. cannot be managed without escalation through alert levels)?

Attached: 'Frequency of Large Outbreak's' paper

4. **Proposed next priorities for the modelling program (Ryan W)**

Purpose: For the Governance Group to provide feedback on of longer-term priorities for the modelling work program.

Context: TPM is in the process of developing a forward work programme to guide their next funding contract. To help guide TPM's work program, the Steering Committee has collectively identified the following priorities:

- Short term, and already underway:
  - Continuing to engage with TPM to refine the 'frequency of large outbreaks' paper (item 3) to understand how different policy toolkits affect risk,
- Longer term:
  - Country specific modelling of COVID risks in the Pacific associated with reopening at different stages of the vaccine rollout,
  - Regional/demographic impacts of reopening given differing vaccination rates,
  - Understanding what the models imply in terms of system capacity (e.g. testing and tracing) and whether these are realistic, and
  - Understanding the impact of additional public health responses on reopening risk (e.g. use of rapid tests).

Attached: Future modelling questions and their relative priority

5. **Any other business (Bryan)**

Purpose: To discuss any outstanding matters. This could include:

- Next steps for TPM funding arrangements.

Note: This paper is a draft and has not yet undergone formal peer review

Frequency of Serious Outbreaks of COVID-19 in a Partially Immune Population (Cover Sheet)

Abstract

We quantify the expected frequency of COVID-19 outbreaks that reach 50 cases (defined as a "serious outbreak") under varying international arrival rates and characteristics. The implications of different border policies such as requiring arrivals to be vaccinated, self-isolate, or take a test on arrival are considered. A simple interactive Excel worksheet has been produced that allows policymakers to test their own scenarios.

Key Assumptions

- Baseline reproduction number (in the absence of vaccination) $R_0 = 3.0$
- Vaccine effectiveness against infection $e_I = 70\%$
- Vaccine effectiveness again transmission given infection $e_T = 50\%$
- The infection time of infected arrivals is distributed randomly within a 14-day period prior to arrival.
- Unless otherwise stated, moderately effective contact tracing is assumed for all scenarios and does not depend on vaccination status.
- 14-day MIQ with routine tests, as per current policy, is 100% effective in preventing community cases.

Key Results

- In a non-vaccinated population, and with no quarantine or testing requirements for arrivals, approximately 16.3% of non-vaccinated infected arrivals are expected to trigger a serious outbreak. At the end of the Tier 4 vaccine roll out (90% of 15+ year-olds fully vaccinated) this decreases to 3.6%. The introduction of a requirement for 7 days self-isolation and a test on arrival reduces these risks to 4.4% and 0.75% respectively.

- In a non-vaccinated population, and with no quarantine or testing requirements for arrivals, approximately 11% of vaccinated infected arrivals are expected to trigger a serious outbreak. At the end of Tier 4 vaccine roll out, this decreases to 2.0%. The introduction of a requirement for 7 days self-isolation and a test on arrival reduces these risks to 2.6% and 0.33% respectively. Furthermore, given an effective vaccine, these individuals are less likely to be infected at all.
- The largest decrease in risk is achieved through increasing the probability of detecting a symptomatic case. In the baseline scenario this is assumed to be 12%, but if it can be substantially increased (to 80%) then a partial reopening can occur earlier with risk of an outbreak less than 1 per year.
- If this can only be moderately increased (say to 50%) then improved contact tracing can make up some of the difference. However, contact tracing has a smaller effect at lower detection probabilities as outbreaks frequently reach 50 cases before they are detected.

Note: This paper is a draft and has not yet undergone formal peer review

Frequency of Serious Outbreaks of COVID-19 in a Partially Immune Population

Methods

We implement a modified version of the stochastic branching process vaccine model described in [1]. Seed cases representing international arrivals are assumed to be infected within 14-days prior to arrival in New Zealand. Testing-on-arrival of travellers can be implemented and these tests are assumed to have a probability of returning a positive result dependent on the time since infection according to [2]. Parallel work is ongoing to quantify test sensitivity in New Zealand but we do not expect this will significantly change any conclusions. A requirement for self-isolation on arrival can also be implemented (typically for 7 days) and is assumed to be 80% effective at preventing onward transmission.

The **probability that an imported case triggers a serious outbreak**, denoted $\boldsymbol{P_c}$**,** is then estimated. For this work, we define a **serious outbreak** as one where the modelled outbreak size reaches 50 cases in the absence of population-level controls. We use 50 cases as an upper limit to represent the fact that the performance of the contact tracing system is likely to deteriorate as the number of cases increases. The subscript c in P_c refers to the specific characteristics that define the arrival and the isolation/testing requirements that apply to them. Examples of characteristics include “not vaccinated, no isolation, no test”, or “vaccinated, 7-day isolation, test on day 0”.

All scenarios assume effective case isolation and contact tracing begin once an outbreak has been detected, corresponding to an approximate 40% reduction in R post-outbreak detection. P_c reflects the probability that these measures are not sufficient to control the outbreak. We do not model any decreasing effectiveness of contact tracing as the number of imported cases increases, so scenarios with frequent outbreaks will be optimistic.

The expected number of outbreaks N over a fixed time period that require population-level controls is then given by:

$$E[N] = \sum_{c} M_c P_c$$

where M_c is the number of arrivals over the time period with characteristics c. Once P_c has been estimated for each set of characteristics of interest, this equation can be easily used to quantify the effect of different arrival rates.

For illustration, we consider the three border re-opening scenarios similar to those listed in policy document *4429565 Initial view on policy questions for modelling*:

a) Stringent Border Controls: Vaccinated travellers self-isolate for 7 days, 14 day MIQ for others. Test on arrival of all travellers.
b) Relaxed Border Controls: Vaccinated travellers enter without restrictions, non-vaccinated travellers self-isolate for 7 days. Test on arrival of all travellers.
c) No Border Controls: Full reopening without restrictions. No testing of arrivals.

Estimated P_c values for the individuals identified in these scenarios are outlined in Table (2).

For each border risk scenario we consider the monthly number of **serious outbreaks** that are expected to occur under two arrival rates: 500,000 per month with 1% prevalence in non-vaccinated individuals (approximately modelling a wide opening to all but very high risk countries), and 100,000 per month with 0.1% prevalence in non-vaccinated individuals (approximately modelling a narrower opening to low-risk countries only). These are crude estimates only used for example. For comparison, there were an average of 591,000 monthly arrivals in 2019. Strictly speaking we are discussing periods equal to 1/12th of a year, i.e. a "month" is assumed to consist of 30.4 days.

Results are presented under the following population vaccination rollout assumptions: there is a maximum achievable vaccination coverage of 90% in any one age group, starting with over 65-year-olds, then 15-64 year-olds, and finally under 15-year olds. The proportion of arrivals that are vaccinated is also varied.

Remaining key assumptions and parameters are outlined in Table 1.

Parameter	Value	Notes
R_0	3.0	Sensitivity to test values of 2.0 and 4.5
Probability of detecting symptomatic case pre-outbreak detection	$p_{detect}^{pre} = 12\%$	These are all measures of contact tracing effectiveness. Sensitivity to test various values.
Probability of detecting symptomatic case post-outbreak detection	$p_{detect}^{post} = 50\%$	
Probability of contact tracing a case	$p_{trace} = 70\%$	
Delay **from exposure** to isolation due to contact tracing	$T_{trace} \sim Exp(6\ days)$	
Delay **from onset** to isolation due to symptomatic detection	$T_{detect} \sim Exp(3\ days)$	
Effectiveness of self-isolation of arrivals	80%	Allows for "leaky" self-isolation
Infection time of seed case	Uniformly randomly within 14 days prior to arrival	Any assumed "prevalence" of incoming travellers should reflect this.
Vaccine Effectiveness	Against infection: 70% Against transmission given infection: 50% Against disease (overall): 95%	Assumed to be the same in both arrivals and domestic. In reality it is likely vaccine effectiveness in arrivals will vary significantly.

Table 1. Assumed parameters. Some have been omitted for brevity, see [1] for full description of the model and all parameters. Isolation due to contact tracing and/or case detection is assumed to be 100% effective.

Results

We begin by estimating P_c for various characteristics without vaccination and at three key staging points of the vaccine rollout identified in the policy A3:

1. End of Tier 2 Rollout – 9.9% of total population (18% of 65+, 10.8% of 15-64)
2. End of Tier 3 Rollout – 43.6% of total population (90% of 65+, 45% of 15-64)
3. End of Tier 4 Rollout – 73.0% of total population (90% of 15+)

The results are presented in table (2).

		P_c – Probability Arrival Results in Serious Outbreak			
Characteristics of Arrival		*No Vaccinations*	*End of Tier 2*	*End of Tier 3*	*End of Tier 4*
Not Vaccinated	None	16.28%	15.10%	9.89%	3.58%
	Test on arrival	10.42%	9.63%	6.46%	2.28%
	7-day isolation and test on arrival	4.40%	3.94%	2.33%	0.75%
Vaccinated	None	10.99%	9.91%	5.95%	2.00%
	Test on arrival	7.19%	6.54%	4.07%	1.30%
	7-day isolation and test on arrival	2.61%	2.19%	1.25%	0.33%

Table 2. Probability that an infected arrival with given characteristics triggers a serious outbreak. For comparison, it has been estimated from analysis of genome sequencing data that 19% of infected arrivals lead to onward transmission in the period prior to Alert Level 4 in March 2020 [3]. Effective case isolation and contact tracing is assumed but no further controls are implemented. Results are the proportion of 100,000 model simulations in which there were at least 50 cumulative infections.

These results show that at the end of tier 4 (90% of 15+ vaccinated), with no population-level restrictions, there are 36 serious outbreaks in the model for every 1,000 non-vaccinated infected arrivals. For arrivals vaccinated with a vaccine that has the same effectiveness as the Pfizer vaccine, this drops to 20 serious outbreaks per 1,000 infected arrivals. These numbers are not directly comparable, however, as a vaccinated arrival is less likely to be infected in the first place.

All else held equal, if the fraction of international arrivals that are infected is ρ, and a fraction v of all arrivals are vaccinated with a vaccine that is e_I effective against infection, then the expected prevalence in *vaccinated arrivals* is $\frac{(1-e_I)\rho}{1-e_I v}$ and the expected prevalence in *non-vaccinated arrivals* is $\frac{\rho}{1-e_I v}$.

We now use this with the P_c values in Table (2) to estimate the number of monthly outbreaks under two different arrival rates. In both scenarios we assume 80% of arrivals are vaccinated and $e_I = 70\%$ in vaccinated arrivals.

1. High Arrivals: 500,000 per month with 1% prevalence in non-vaccinated individuals (0.3% prevalence in vaccinated). This reflects a wider opening to all but very high risk countries. Under this scenario there are an expected 1,000 infected non-vaccinated arrivals per month and 1,200 infected vaccinated arrivals.
2. Low Arrivals: 100,000 per month with 0.1% prevalence in non-vaccinated individuals (0.03% in vaccinated). This reflects an opening to low risk countries only. Under this scenario there are an expected 20 infected non-vaccinated arrivals per month and 24 infected vaccinated arrivals.

The three border risk control settings outlined in the methods section are used.

		Number of Serious Outbreaks per Month			
		No Vaccinations	*End of Tier 2*	*End of Tier 3*	*End of Tier 4*
High Arrivals (500,000 per month with 1% prevalence in non-vaccinated)	Stringent Border Controls	31.37	26.29	14.94	3.95
	Relaxed Border Controls	130.27	117.78	72.09	23.00
	No Border Controls	294.61	269.95	170.22	59.86
Low Arrivals (100,000 per month with 0.1% prevalence in	Stringent Border Controls	0.63	0.53	0.30	0.08
	Relaxed Border Controls	2.61	2.36	1.44	0.46

non-vaccinated)	No Border Controls	5.89	5.40	3.40	1.20

Table 3. Number of serious outbreaks per month under two arrival rates and three border control scenarios. We **assume that 80% of all arrivals are vaccinated** and the 14 day MIQ used for non-vaccinated arrivals in the low-risk controls is 100% effective at preventing onward transmission. MIQ capacity is not considered, so for the stringent border control scenarios where 14 days in MIQ is required for non-vaccinated individuals, the true arrival rate will likely be lower.

For comparison, there have been two outbreaks since the start of August 2020 that triggered population-level restrictions (Alert Level 3) as opposed to being controlled with case isolation and contact tracing alone. Although one of the outbreaks did not reach the required 50 cases to be considered “serious”, it may have done if population level controls were not used. Based on this, there have been around 0.2 outbreaks per month. This empirical outbreak rate is between the predicted outbreak rates for the stringent controls and relaxed controls in a low arrivals scenario at the end of Tier 4. In other words, stringent border controls would need to remain in place at the end of Tier 4 of the vaccine rollout to avoid an increase in the risk of serious outbreaks requiring population-level restrictions.

Results on the expected number of outbreaks per month as a function of the percentage of the population fully vaccinated are presented in figure (1) under the same vaccine rollout assumptions as previously: up to 90% of each age group is vaccinated, starting with 65+, then 15-64, and finally under-15-year-olds. In addition to the scenario where 80% of arrivals are vaccinated, we also consider the results when 50% of arrivals are vaccinated.

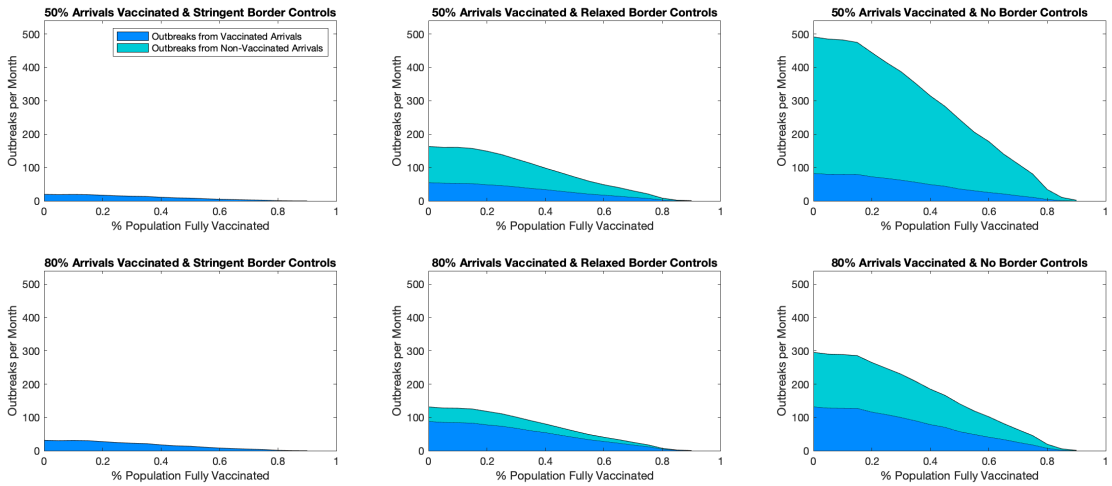

Figure 1. Number of serious outbreaks per month under **high arrival rates and 1% prevalence in non-vaccinated**. Upper plots assume 50% of arrivals are vaccinated, and lower plots assumed 80% of arrivals are vaccinated (as per Table 3).

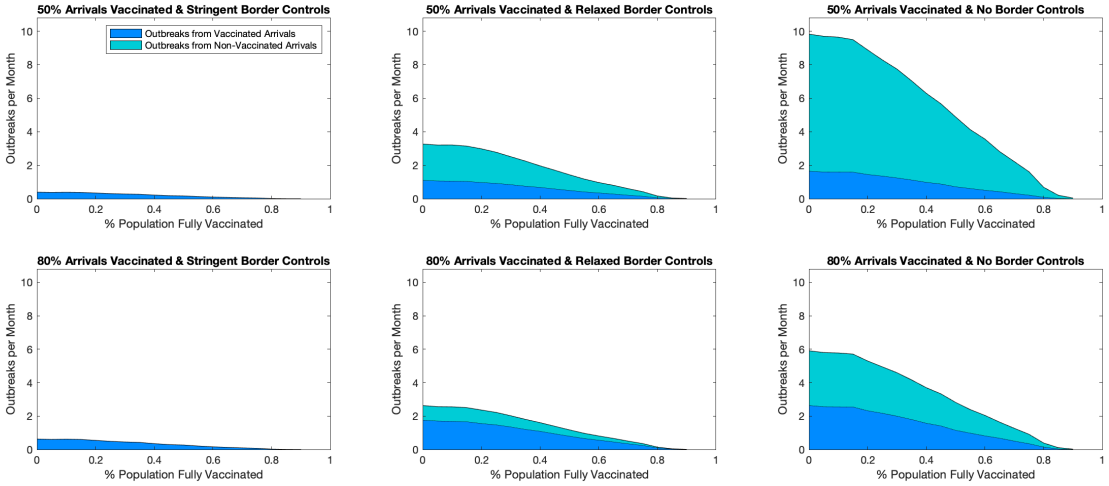

Figure 2. Number of serious outbreaks per month under **low arrival rates and 0.1% prevalence in non-vaccinated**. Upper plots assume 50% of arrivals are vaccinated, and lower plots assumed 80% of arrivals are vaccinated (as per Table 3). As arrival rates simply scale the overall results, the shape of these plots is the same as Figure (1), just with different y-axis values.

An excel document *OutbreakFrequencyTool.xlsx* allows table (3) and figure (1) to be reproduced under user-chosen arrival characteristics and arrival rates. This document also includes all underlying data used above and in the scenario analysis.

Scenarios

We test a few key policy scenarios, focusing on the effect of case detection and contact tracing. Sensitivity to a few key epidemiological parameters is also tested. All scenarios considering the number of outbreaks per month assume 80% of arrivals are vaccinated.

Improved Case Detection

Characteristics of Arrival		P_c – Probability Arrival Results in Serious Outbreak			
		No Vaccinations	*End of Tier 2*	*End of Tier 3*	*End of Tier 4*
Not Vaccinated	None	6.70%	5.67%	2.51%	0.47%
	Test on arrival	4.64%	3.89%	1.71%	0.37%
	7-day isolation and test	1.45%	1.24%	0.45%	0.07%
Vaccinated	None	4.07%	3.47%	1.35%	0.21%
	Test on arrival	2.86%	2.36%	0.93%	0.17%
	7-day isolation and test	0.88%	0.70%	0.26%	0.04%

Table 6.

		Number of Serious Outbreaks per Month			
		No Vaccinations	*End of Tier 2*	*End of Tier 3*	*End of Tier 4*
High Arrivals (500,000 p/m with 1% prev in non-vax)	Stringent Border Controls	10.57	8.34	3.11	0.44
	Relaxed Border Controls	48.80	40.74	15.67	2.75
	No Border Controls	115.87	98.32	41.39	7.22
Low Arrivals (100,000 p/m w/ 0.1% prev in non-vax)	Stringent Border Controls	0.21	0.17	0.06	0.01
	Relaxed Border Controls	0.98	0.81	0.31	0.06
	No Border Controls	2.32	1.97	0.83	0.14

Table 7.

Increasing the probability of detecting any symptomatic case to 80% (from 12%) and reducing the delay from onset to detection to 1 day (from 3 days) allows the contact tracing system to act earlier, preventing a higher proportion of outbreaks from reaching 50 cases. Achieving such high detection probabilities would involve an extremely large public health effort, and at the very least would require testing **all** symptomatic individuals in the population multiple times. **These results should be viewed as an absolute upper bound on risk reduction by initial case detection.**

If these detection probabilities are achievable, at the end of tier 3, a reopening to vaccinated individuals from low risk countries with 7 days self-isolation and a test on arrival is expected to trigger fewer than one serious outbreak per year.

Improved Contact Tracing

Characteristics of Arrival		P_c – Probability Arrival Results in Serious Outbreak			
		No Vaccinations	*End of Tier 2*	*End of Tier 3*	*End of Tier 4*
Not Vaccinated	None	14.12%	12.45%	7.40%	2.43%
	Test on arrival	8.94%	8.09%	4.84%	1.70%
	7-day isolation and test	3.60%	3.23%	1.69%	0.47%
Vaccinated	None	9.18%	8.12%	4.52%	1.33%
	Test on arrival	6.05%	5.25%	3.07%	0.95%
	7-day isolation and test	2.15%	1.77%	0.94%	0.26%

Table 8.

		Number of Serious Outbreaks per Month			
		No Vaccinations	*End of Tier 2*	*End of Tier 3*	*End of Tier 4*
High Arrivals (500,000 p/m with 1% prev in non-vax)	Stringent Border Controls	25.76	21.29	11.26	3.17
	Relaxed Border Controls	108.65	95.32	53.69	16.03
	No Border Controls	251.30	221.95	128.32	40.21
Low Arrivals (100,000 p/m w/ 0.1% prev in non-vax)	Stringent Border Controls	0.52	0.43	0.23	0.06
	Relaxed Border Controls	2.17	1.91	1.07	0.32
	No Border Controls	5.03	4.44	2.57	0.80

Table 9.

Increasing the probability of tracing an infected contact to 95% (from 70%) and decreasing the mean delay from exposure to tracing to 3 days (rather than 6) increases the reduction in R from contact tracing from 40% to 74%. This is sufficient to control any outbreak with $R_0 < 3.8$, eventually, but isn't always sufficient to prevent it from reaching 50 cases. With standard symptomatic detection probabilities of 12% (pre-outbreak detection), outbreaks sometimes aren't detected until they have reached 50+ cases.

Even with improved contact tracing, the only scenario in which less than 1 serious outbreak is expected to occur per year is with stringent border controls and low arrival rates at the end of Tier 4.

Improved Case Detection and Contact Tracing

Characteristics of Arrival		P_c – Probability Arrival Results in Serious Outbreak			
		No Vaccinations	*End of Tier 2*	*End of Tier 3*	*End of Tier 4*
Not Vaccinated	None	9.73%	8.34%	4.04%	0.92%
	Test on arrival	6.40%	5.49%	2.75%	0.61%
	7-day isolation and test	2.35%	1.96%	0.81%	0.17%
Vaccinated	None	6.21%	5.14%	2.19%	0.50%
	Test on arrival	4.09%	3.42%	1.49%	0.34%
	7-day isolation and test	1.32%	1.06%	0.41%	0.09%

Table 10.

		Number of Serious Outbreaks per Month			
		No Vaccinations	*End of Tier 2*	*End of Tier 3*	*End of Tier 4*
High Arrivals (500,000 p/m with 1% prev in non-vax)	Stringent Border Controls	15.80	12.70	4.86	1.07
	Relaxed Border Controls	72.64	60.58	26.03	5.84
	No Border Controls	171.82	145.09	66.58	15.22
Low Arrivals (100,000 p/m w/ 0.1% prev in non-vax)	Stringent Border Controls	0.32	0.25	0.10	0.02
	Relaxed Border Controls	1.45	1.21	0.52	0.12
	No Border Controls	3.44	2.90	1.33	0.30

Table 11.

This time we consider moderately improved case detection and contact tracing together. We assume the probability of detecting a symptomatic case (before outbreak detection) is 50%, with a mean delay of 2 days from symptom onset. The probability of tracing an infected contact is 80% with a mean delay of 4 days from exposure. Such a contact tracing system reduces R by 56% post-detection.

These results are relatively similar to the in the "Improved Case Detection" section. That is, the increased effectiveness in the contact tracing system from increasing p_{Trace} from 70% to 80% and decreasing mean t_{Trace} from 6 days to 4 days, makes up for the shift from $p_{Detect} = 80\%/t_{Detect} = 1\ day$ (in "Improved Case Detection") to $p_{detect} = 50\%/t_{detect} = 2\ days$.

Discussion

Results suggest that at the end of the Tier 4 vaccine roll-out, a partial reopening to low risk countries scenario with stringent border controls (80,000 vaccinated arrivals per month that self-isolate for 7-days and take a test on arrival) carries the risk of a serious outbreak every 12.5 months. Removing the requirement to self-isolate increases this to a serious outbreak every 2.2 months.

This risk can be further reduced through a variety of public health measures. This most substantial decrease in risk from any single intervention comes from improved symptomatic case detection. If this was increased to 80%, the same low-risk low-arrivals with stringent border controls scenario carries the risk of a serious outbreak every 4.8 months. Furthermore, at the end of the Tier 4 rollout, isolation and testing requirements of all arrivals could be removed, with the serious outbreaks expected to occur only every 7.1 months (this also assumes 20,000 non-vaccinated arrivals per month). Such high detection probabilities may be infeasible in practice, however a moderate increase in case detection, if accompanied by improved contact tracing, can achieve similar results.

Decreasing the frequency of serious outbreaks is not the only advantage that vaccination provides. We know from [1] that we can also expect:

- Reduced stringency of population-level controls to eliminate an outbreak
- Shorter times to elimination at any given level of control
- Reduced negative health outcomes from any outbreak (all else held equal)

The final point is true even fairly early in the roll out as the most vulnerable are vaccinated first. This may mean that more frequent outbreaks are more tolerable, especially as less strict controls will be required to achieve elimination in similar time frame.

We have not considered any heterogeneities in vaccine coverage or any other parameters. Table 16 considers factors such as these and the effect they may have on the frequency of serious outbreaks.

Factor	Effect on Frequency	Description
Heterogeneities in vaccine coverage	Depends	If border-facing communities have higher-than-average vaccine coverage then the frequency of serious outbreaks will decrease (and vice-versa).
Regional Variation in R_0	Depends	If border-facing communities have higher values of R_0 then the frequency of serious outbreaks will increase (and vice-versa).
Correlation between Vaccination and Testing	Increase	It is conceivable that communities with low vaccination rates are likely to also have low testing rates. This effectively decreases the overall probability of detecting a case, increasing the frequency of serious outbreaks.
Temporal Variation in R_0	Depends	As vaccination continues, contact between under 16 year olds becomes more important for overall spread. During periods of school holidays (for example), contact within this group is reduced, which may decrease the frequency of serious outbreaks. There may also be a seasonal effect.

Table 16. Possible additional factors that may affect the frequency of serious outbreaks not considered in the modelling.

For the steering group:

Going forward, it is likely that future work (for example, considering different contact structures) will have implications on the frequency of serious outbreaks. It may be useful to reproduce some of the results in this paper under various other assumptions. An idea of one-or-two scenarios to focus on would be useful. E.g. should we focus on re-opening to a handful of very-low-risk countries, or consider a more general re-opening? Which restrictions on vaccinated and non-vaccinated are likely to be realistic policies?

References

1. Steyn, N., et al., *A COVID-19 Vaccination Model for Aotearoa New Zealand.* Not Published, 2021.
2. Kucirka, L.M., et al., *Variation in False-Negative Rate of Reverse Transcriptase Polymerase Chain Reaction-Based SARS-CoV-2 Tests by Time Since Exposure.* Ann Intern Med, 2020. **173**(4): p. 262-267.
3. Geoghegan, J.L., et al., *Genomic epidemiology reveals transmission patterns and dynamics of SARS-CoV-2 in Aotearoa New Zealand.* Nat Commun, 2020. **11**(1): p. 6351.

Future modelling questions and their relative priority

Objectives for the Governance Group meeting

At the meeting of 13 July 2021, the Steering Committee is seeking the Governance Group's feedback on the next set of priorities for the modelling work program. This will ultimately be used to inform a work programme to be agreed with TPM for their next contract period.

Context for this document: Aligning modelling priorities with the policy process and future decisions

As directed by the Governance Group, the Steering Committee aims to ensure that modelling outputs from a range of sources can inform future policy decisions over the coming months. Examples of the specific types of questions which decision-makers might need to answer over the next 6 months are:

- Should we open to a volume/category of traveller from a particular place?
- Do we need to invest – with some lead-in time/costs – in additional capacity or different capabilities to the status quo in order to manage future risks?

Through a modular approach to the modelling and analysis, we can bring together a complete picture to inform decision-makers at the right time, as one factor of several in their decision-making processes.

The Reconnecting New Zealanders strategy work programme is organised beneath a number of themes. Across each of these themes sit different aspects of the modelling. They are:

- What are the public health conditions that will enable different reconnection options while keeping New Zealanders safe from COVID-19?
- Which countries, cohorts or individuals will be allowed to enter and leave New Zealand under what settings, and when?
- What does the long-term management of COVID-19 look like (what should citizens expect and what risks will we need to continue to manage)?
- How do our health and border systems need to adapt, across different stages of vaccination and reconnection, in order to minimise risks and achieve our objectives?

Under the reconnecting New Zealand work program, Cabinet has also recently requested additional advice in August including additional detail on:

- the public health conditions that can allow movement across the phases in the reconnection strategy, informed by independent advice from the COVID-19 Strategic Public Health Advisory Group;
- a more sophisticated traveller approach at each stage of the strategy, including additional data and modelling to inform a country-of-origin and traveller-level risk assessments, as well as options for the sequencing of traveller groups and approaches to managing traveller volumes; and
- a more detailed assessment of the proposal to start moving towards a traveller-centric approach with an initial focus on amended entry requirements for fully vaccinated New Zealanders wishing to leave and return.

With these themes and report back dates in mind, this document sets out the Steering Committee's priority questions to be informed by modelling, with estimated complexity and priority used to inform a future work programme.
These are separated out into questions regarding:

- external risk settings (e.g. from which countries does NZ allow travellers),
- border risk settings (e.g. what combinations of testing and isolation can be used) and
- broader domestic policy settings (e.g. capacity for contact tracing, use of vaccination as a breakout suppression tool).

Additional questions that fall outside these general categories are separately captured at the end of the document.

Proposed priorities

The key priorities are outlined here, with more detail in the attached annex

Short term

To inform advice to Cabinet in August, the Modelling Steering Committee have identified two immediate priorities for the modelling work program with delivery by end-July 2021, with work already commissioned and underway. These are:

- Supporting the Ministry of Health in their engagement with Professor Richard Arnold on modelling risk from arrivals, including understanding how outcomes change under different border treatments (e.g. treating vaccinated arrivals differently to unvaccinated arrivals). This work is reflected in the table with questions regarding the overseas environment.

- Engaging with TPM on their 'frequency of large outbreaks' model, to understand how different policy 'toolkits' (both at the border and across the population) affect the occurrence of large outbreaks once the border is opened more broadly.

Longer term

To end-2021, subject to TPM's funding, the Committee considers that using modelling to enhance our understanding of the following issues should be priorities.

- Country specific modelling of COVID-19 risks at different stages of vaccination rollouts for the Pacific (the Prime Minister has indicated that this is a priority),
- Region/demographic specific modelling to understand how risks differ across different population groups (e.g. Maori and Pacifica populations) at each stage of the vaccination rollout.
- Understanding the 'real world' implications of delivering on the models' implied levels of testing, contact tracing and ICU capacity (for example), to ensure that they either fit within existing capacity or prompt additional work on potential expansion.
- Modelling additional combinations of public health responses and understanding how they effect risk across the vaccination rollout. For example, how the use of lower-sensitivity 'rapid tests' at higher rates, or additional spacing in vaccine delivery, effect outbreak size and frequency.

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Annex: more detail on proposed modelling piorities

Questions/functions related to the overseas environment for the network/branching model (immediate priorities highlighted in green)

Question/function	Complexity/What is needed to deliver?	Relative priority	When to commission?	Other overlapping considerations/context
External risk: the rate of the offshore prevalence of COVID-19 and the effects on New Zealand (e.g. if 10,000 people from X country have a Y prevalence of COVID-19, how many large outbreaks would there be in New Zealand?) *This is related to question below re. vaccine take up in different jurisdictions. For SC: Can these be consolidated?*	Moderate Data on the prevalence of COVID-19 in different countries. Assumptions would then need to be made about the numbers of travellers from different countries. We also need to be able to identify how quickly change in prevalence turns up in traveller risk (is this just related to how quickly an exposed person becomes infected and infectious, or do we also need to consider behavioural factors?)	High Country specific risk can inform when NZ opens up to specific countries, or how the countries we open to changes over time in respect to their own domestic conditions.	Commission ASAP. Work to be led by Health and Richard Arnold.	MOH has developed a proposal for a new Country Risk Assessment framework. The framework will require the monitoring of indicators such as case numbers and vaccine uptake. This is important for August report back to Cabinet.
External risk: the impact of lower vaccination uptake/different types of vaccination uptake (e.g. AZ vs. Pfizer) in different countries/populations on outbreaks in NZ. *This is related to question above re. prevalence in different jurisdictions.*	Moderate Officials to develop input assumptions. Model may need to be augmented to separate out arrivals by country of origin.	Moderate/High Important for the same reasons as above, but not as relevant for the August cabinet paper.	Depends on availability of inputs, but aim for August.	As above.
External risk: model specific risks associated with Pacific countries (i.e. with inputs for country-specific population and contact structures)	Moderate/High (*unsure on availability of data*) Requires data on population and contact structures for relevant countries.	High Pacific countries are most likely to be viable options for any extension of QFT.	Depends on availability of inputs, but aim for August.	We understand that Minister Hipkins has directed officials to explore options for one-way QFT with certain Pacific jurisdictions.

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Questions/functions related to border settings for network/branching model (immediate priorities highlighted in green)

Question/function	Complexity/What is needed to deliver?	Relative priority	When to commission?	Other overlapping considerations/context
How does the number of large outbreaks change if we only allow vaccinated persons over the border?	Low Can be delivered with the existing model by officials.	High	N/A. Officials can complete this analysis using the available spreadsheet.	
For the frequency of large outbreaks paper, can a new parameter for probability of detecting symptomatic cases pre-outbreak among recent arrivals be added? This would capture policies like follow-up calls and stronger guidance for recent arrivals.	Low/moderate Can be delivered with existing model. A range of probabilities include: 12%, 25%, 50% and 80% which capture different public health options.	High	Commission ASAP. Work to be led by TPM.	This is important for August report back to Cabinet.
For the frequency of large outbreaks paper, can we include a 'relaxed plus' control, where vaccinated arrivals isolate until they have the results from the COVID-19 test that they took upon arriving in NZ?	Low Can be delivered with the existing model.	High	Commission ASAP. Work to be led by TPM.	This is important for August report back to Cabinet.
For the frequency of large outbreaks paper, can we model adding a test after seven days (to the test on arrival) for those who aren't isolating (i.e. 'relaxed plus #2')?	Low Can be delivered with the existing model.	High	Commission ASAP. Work to be led by TPM.	This is important for August report back to Cabinet.

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Questions/functions related to broader domestic policy settings for network/branching model (immediate priorities highlighted in green)

Question/function	Complexity/What is needed to deliver?	Relative priority	When to commission?	Other overlapping considerations/context
Model the 'probability and severity' of severe outbreaks when subject to different 'toolkits' of policy responses (e.g. isolation at home, contact tracing, vaccination).	Moderate Officials need to agree what constitutes each desired 'package' of public health responses.	High	Commission ASAP. Work to be led by TPM.	This is important for August report back to Cabinet
Model the effect of increased detection capability (e.g. rapid tests, wastewater detection) on COVID-19 outbreak numbers (i.e. where the probability of pre-detection is more than 12%)? *This could be combined with the removal of a self-isolation requirement post-test/pre-results.*	High Officials to lead. Needs to be informed by real-world constraints on testing capacity (and the extent to which rapid tests may be part of the reopening strategy/public health controls going forward). Officials also need to consider what value of probability of pre-detection is reasonable?	Medium	August. Officials need to determine a reasonable detection architecture based on available resources.	
Model the effect of a portion of the population only receiving one vaccine shot/larger gaps between the first and second shot (e.g. vary the percentage of population of who receive the vaccination to account for lower average effectiveness).	Low/moderate Reasonable estimates of the population who would only receive: one shot vs two shots vs no shots, at different stages of the vaccination rollout.	Medium	August, once members have agreed reasonable input assumptions.	

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Other/broader requirements and questions

Question/function	Complexity/What is needed to deliver?	Relative priority	When to commission?	Other overlapping considerations/context
Spreadsheet tool: NZ version of University of Melbourne repeat game model	High Officials to lead. Engage with UM – may not require TPM.	High Important to inform policy decisions around reopening as vaccine roll-out progresses and take-up assumptions of the vaccination rate, per population, can be varied.	N/A. Agencies to separately engage with University of Melbourne.	
Use network model to determine how different outbreaks could play out in different regions. Ideally outputs should be available at the local level to understand distributional impacts of reopening.	High Estimated vaccine take up in different communities. Estimates of contact between and within communities.	High Important to understand impact of reopening on Maori/Pacifica and other at risk groups. This can then inform the development of other policies.	August, once members have agreed reasonable input assumptions.	Strong demand from stakeholders for equity & Te Tiriti perspectives to inform policy development.
Comparison of anticipated effects of COVID at population level against other diseases	Low Data on incidence/effect of other diseases (e.g. measles, influenza). Officials lead (potentially MoH) – may not require TPM.	Medium Will help contextualise the models outcomes for Ministers/public and inform proportionate policy responses.	N/A. Agencies to develop separately and present alongside modelling results.	
Use network model to determine how the number of large outbreaks change as NZ progresses through the vaccine rollout.	Moderate Forecast/actual data on vaccine coverage at each stage of the rollout. May require model updates.	High Helps phase reopening against different rollout stages.	August, once members have agreed reasonable input assumptions.	
Understanding how vaccination affects behaviour (e.g. rates of testing and effectiveness of contact tracing). This can be used as an input into the branch model.	Moderate Overseas data if available? Difficult to isolate effect of vaccination on behaviour.	Medium Useful input, but perhaps less determinative to outcomes than packages of public health tools etc.	August/September once better data is available on effect of vaccine.	

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Question/function	Complexity/What is needed to deliver?	Relative priority	When to commission?	Other overlapping considerations/context
Build understanding of how large outbreaks will overlap, to inform assessment of the likely load on NZ health system.	Low/Moderate Can the network model achieve this currently?	Medium Important input, but given current low level of risk appetite, it may not be Ministers highest priority.	August, as additional module for work on 'frequency of large outbreaks'	
Sensitivity analysis: Understanding the full distribution of outbreaks. Perhaps outbreaks of 2-19, 20-49, 50-99 and 100+	Low Officials need to offer alternative definitions of 'large outbreak', but can be completed with existing branching model.	High	August, as additional module for work on 'frequency of large outbreaks'	
Sensitivity analysis: for outbreaks that do not become 'large', report the number of cases that would be detected and number of generations, so that we can consider the likely size that would be required for the contact tracing effort.	Low Can be completed with existing branching model	High	August, as additional module for work on 'frequency of large outbreaks'	
Sensitivity analysis: how do the results change if vaccine efficacy declines over time (either as a result of new variants or time)?	Low/Moderate Limited data currently available on drop off of efficacy (if any).	Medium	Late-August/September, if data becomes available, as an additional module for work on 'frequency of large outbreaks'	

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Question/function	Complexity/What is needed to deliver?	Relative priority	When to commission?	Other overlapping considerations/context
We are interested in adding some new outputs to the model to help give a sense of the testing and contact tracing capacity 'used up' in different scenarios. Some things are not explicitly modelled, so this may have to be inferred from other outputs. We would be interested in: tests used at border per month, tests used in community per month, contacts traced per month. The last one is likely not modelled, but could be inferred from other outputs such as number of cases, number of generations in an outbreak	Moderate/high	High Informs real-world approach to re-opening. Risk needs to be calibrated to the available infrastructure.	Late-August/September, if data becomes available, as an additional module for work on 'frequency of large outbreaks'	

From: Christopher Nees [TSY]
To: Bryan Chapple [TSY]; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; "x@xx ; "x@xx ; "x@xx ; Susie Meade [DPMC]; "x@xx ; "^EDU: Paul Stocks"; ^EXT: Talosaga Talosaga
Cc: Margaret Galt [TSY]; "x@xx ; Bevan Lye [TSY]; George Whitworth [DPMC]; "x@xx ; Kerryn Fowlie; Alastair Cameron [TSY]; Ryan Walsh [TSY]
Subject: Agenda and papers for Modelling Governance Group on Friday
Date: Tuesday, 11 May 2021 4:27:00 PM
Attachments: 4457033_WCA Treasury Presentation May 2021 (002).PDF
4457032_DPMC Vaccines Modelling slide pack.PPTX
4443750_vaccine modelling summary.DOCX
image005.png
image006.png
4457019_Agenda for Modelling Governance Group meeting 14 May 2021.DOCX
image001.png

Kia ora koutou
Please find attached the agenda and papers for Friday's Modelling Governance Group meeting.

Ngā mihi

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-
I do not work on Thursdays.

-

From: Christopher Nees [TSY]
Sent: Wednesday, 5 May 2021 11:31 AM
To: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>; ^MSD: Nic Blakeley <xxx.xxxxxxxxxx@xxx.xxxx.xx>; Cheryl Barnes [DPMC] <Cheryl.Barnes@dpmc.govt.nz>; 'xxxxx.xxxxxx@xxxxx.xxxx.xx' <xxxxx.xxxxxx@xxxxx.xxxx.xx>; 'Ian.Town@health.govt.nz' <xxx.xxxx@xxxxxx.xxxx.xx>; 'xxxxx@xxxxxxxx.xx.xx' <xxxxx@xxxxxxxx.xx.xx>; Susie Meade [DPMC] <xxxxx.xxxxx@xxxx.xxxx.xx>; 'xxxx.xxxx@xxxxxx.xxxx.xx' <Gill.Hall@health.govt.nz>; ^EDU: Paul Stocks; ^Health: Maree Roberts <xxxxx.xxxxxxx@xxxxxx.xxxx.xx>
Cc: Margaret Galt [TSY] <xxxxxxxx.xxxx@xxxxxxxx.xxxx.xx>; 'Pubudu.Senanayakx@xxxxx.xxxx.xx' <xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx>; Bevan Lye [TSY] <Bevan.Lye@treasury.govt.nz>; George Whitworth [DPMC] <xxxxxx.xxxxxxxxx@xxxx.xxxx.xx>; 'xxxx.xxxx@xxxxxx.xxxx.nz' <xxxx.xxxx@xxxxxx.xxxx.xx>; Kerryn Fowlie <xxxxxx.xxxxxx@xxxxxxxx.xxxx.nz>; Alastair Cameron [TSY] <xxxxxxxx.xxxxxxx@xxxxxxxx.xxxx.xx>
Subject: Draft proposed agenda for Covid-19 Modelling Governance Group next Friday

Kia ora koutou

Our proposed agenda for next Friday's Modelling Governance group is below – please let me know if there are other items you want to cover off and we will circulate a final agenda and papers on Monday:

1. Overview of vaccines/borders modelling results and next steps. We have been continuing to engage with TPM as they further develop the work we reported on at the last meeting. We'll cover key results and what is being commissioned from here, for your feedback and direction.

2. Latest context on the international picture. Through our contract with Wigram Capital, they have provided the Steering Group with an updated overview of the global picture looking at vaccine roll outs, effects on case numbers and fatalities, and unpicking the effect of lockdowns vs vaccination on those metrics. We have discussed a 'watch list' of issues to consider (e.g. how Israel's school reopening affects cases, how Sinovac is complicating the global picture, Singapore's continued community transmission, and how India looks to be bending the curve but another wave is inevitable). This is useful context to have in mind as we both consider vaccine efficacy in New Zealand and how borders re-open.

3. The Advisory Group – discussion on its operation and if/how we could support it further.

Ngā mihi

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I do not work on Thursdays.

-----Original Appointment-----
From: Bryan Chapple [TSY] <xxxxx.xxxxxxx@xxxxxxxx.xxxx.xx >
Sent: Friday, 16 April 2021 2:46 PM
To: Bryan Chapple [TSY]; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; 'vince.gxxxxx@xxxxx.xxxx.xx'; 'xxx.xxxx@xxxxxx.xxxx.xx'; 'xxxxx@xxxxxxxx.xx.xx'; Margaret Galt [TSY]; Christopher Nees [TSY]; George Whitworth [DPMC]; Susie Meade [DPMC]; Sam Tendeter [TSY]; 'Gill.Hxxx@xxxxxx.xxxx.xx';

'xxxxxx.xxxxxxxxxx@xxxxx.xxxx.xx'; ^EDU: Paul Stocks; 'maree.roberts@health.govt.nz'
Subject: Covid-19 Modelling Governance Group
When: Friday, 14 May 2021 2:00 PM-2:45 PM (UTC+12:00) Auckland, Wellington.
Where: +TSY 3.34 Poutama -16 (EXT) - MS Teams Link enclosed

Dear attendees,

Agenda and papers will be circulated In advance.

Microsoft Teams meeting

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Kind Regards
Jozef

Jozef Citari | Te Tai Ōhanga - The Treasury
Executive Assistant to Deputy Secretary for Macroeconomics & Growth – Mr. Bryan Chapple

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wigram CapitalAdvisors

COVID-19:

Rodney Jones

5 May 2021

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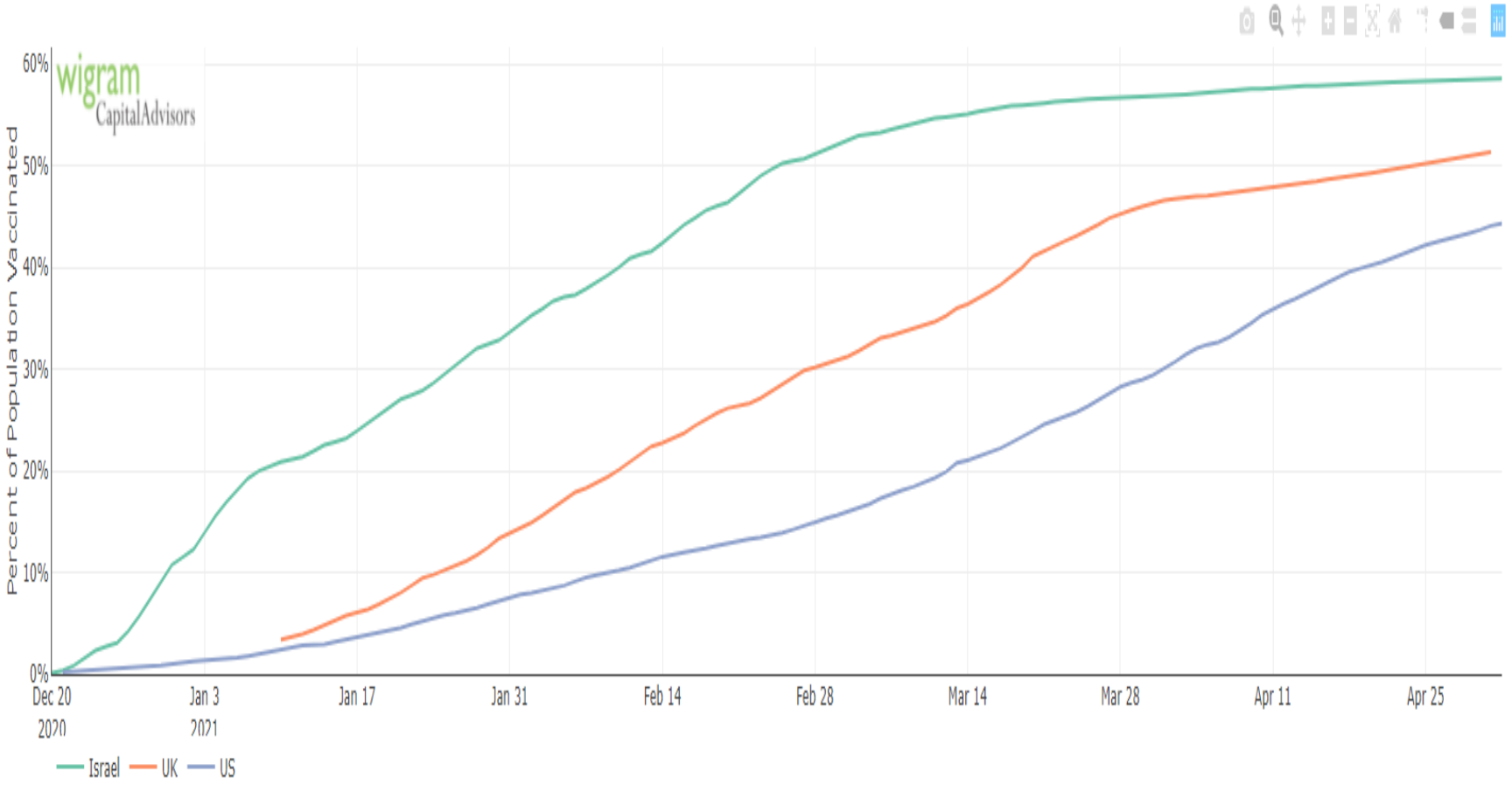
Vaccination Rate

More than 50% of adults in the US, UK and Israel have received the first dose.

55% of Israel's adult population have received the second dose, while in the US and UK are tracking at 30% and 22% respectively.



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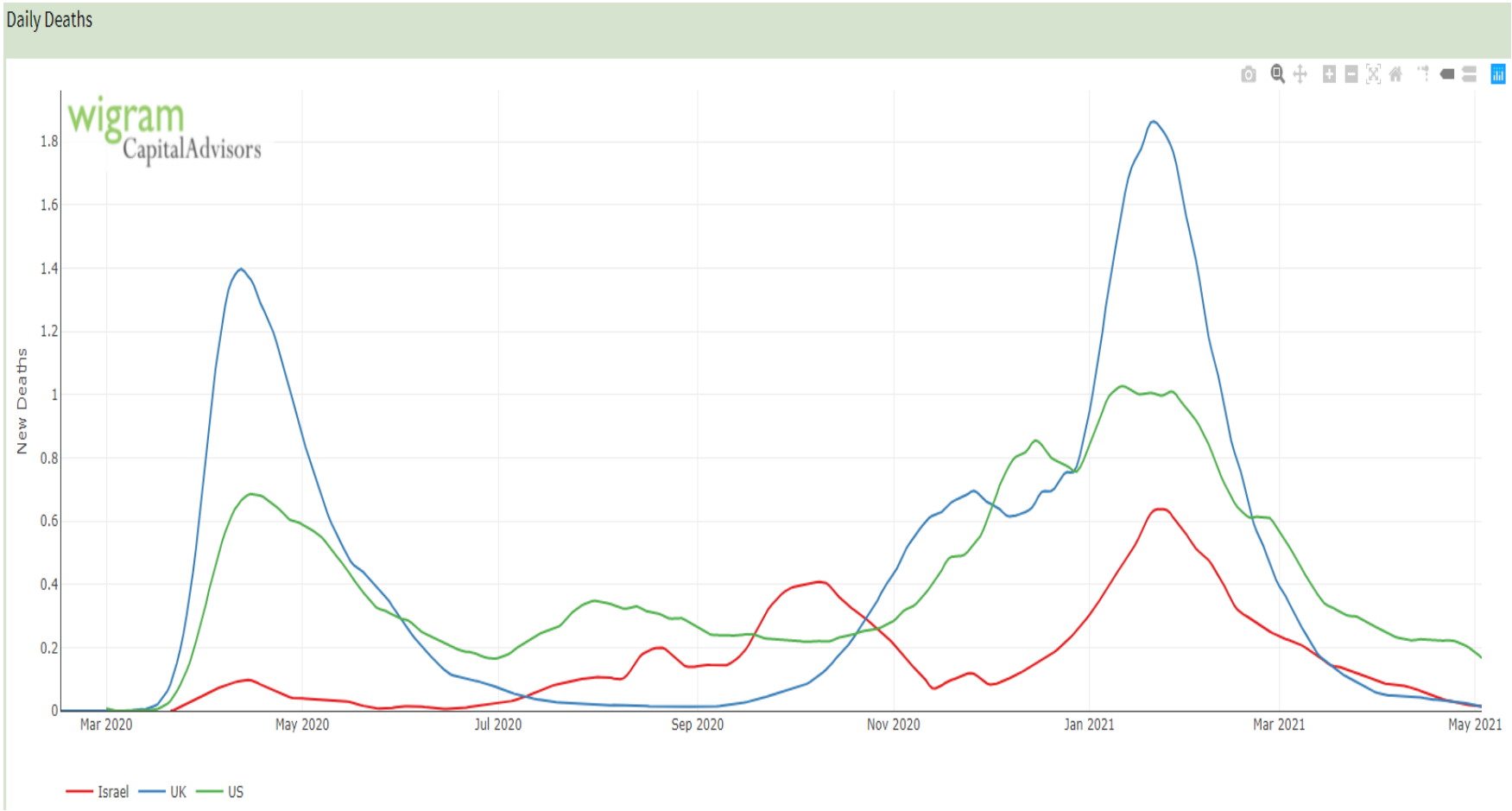
Vaccination Rate

The impact of vaccination rollouts is evident in the case fatality data



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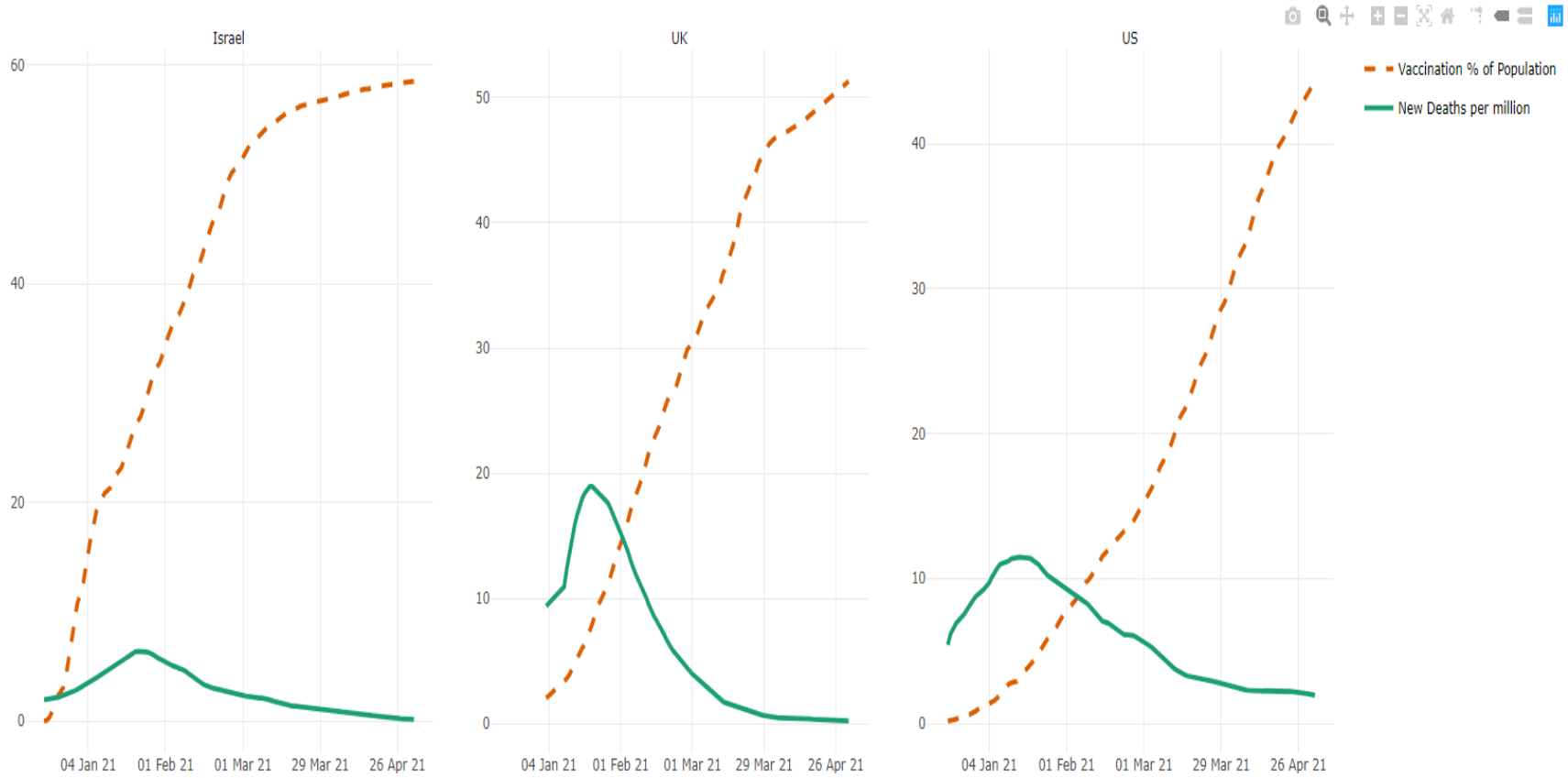
Vaccination Rate

The UK and Israel only reported a single covid death yesterday.

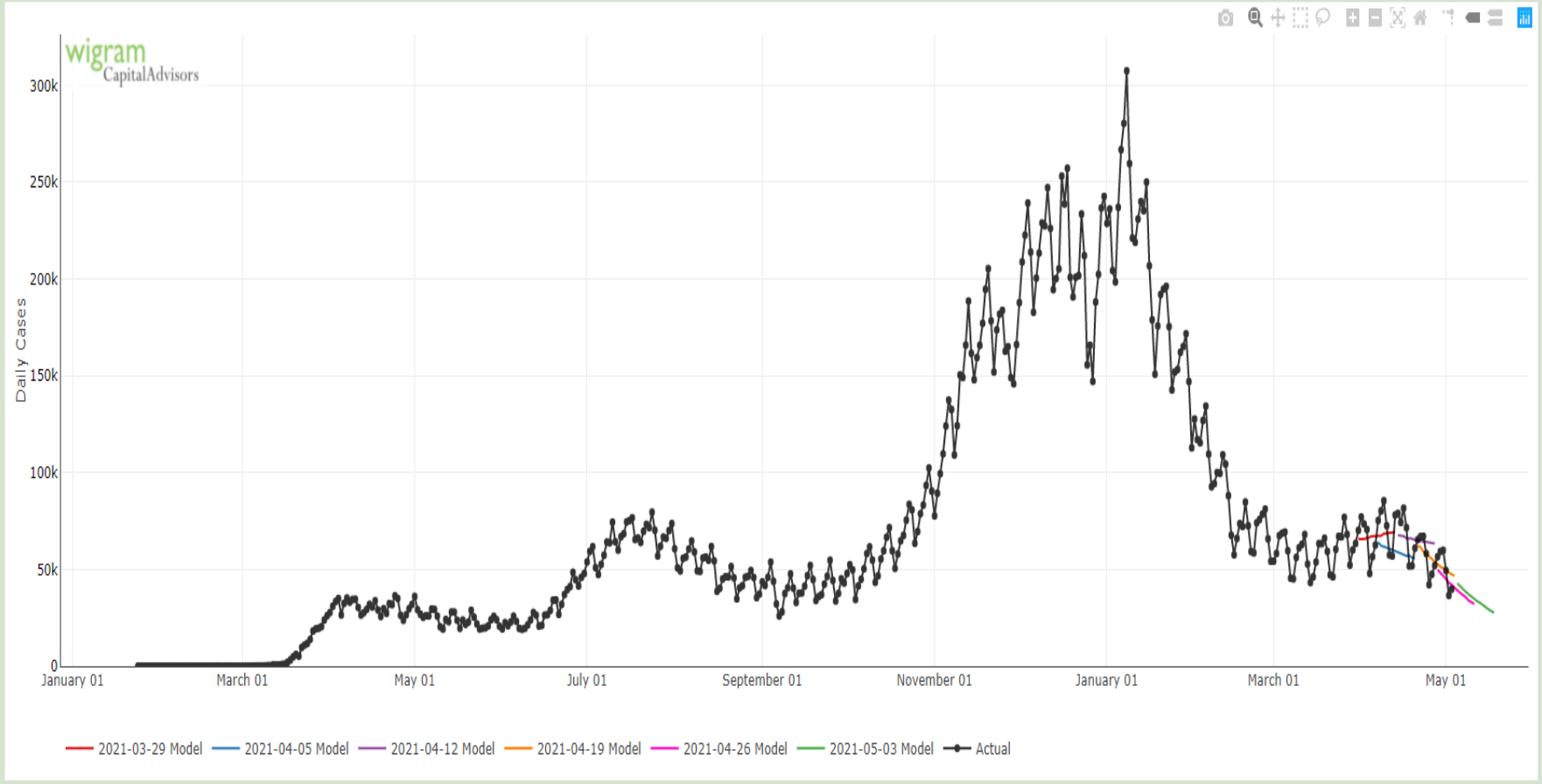
The US daily deaths 7-day-average is tracking the lowest it has been since last year July.



The US

The US continues to track downwards.

Actual and Wigram Modelled Daily Cases in US



Source: Wigram Capital Advisors and Worldometer

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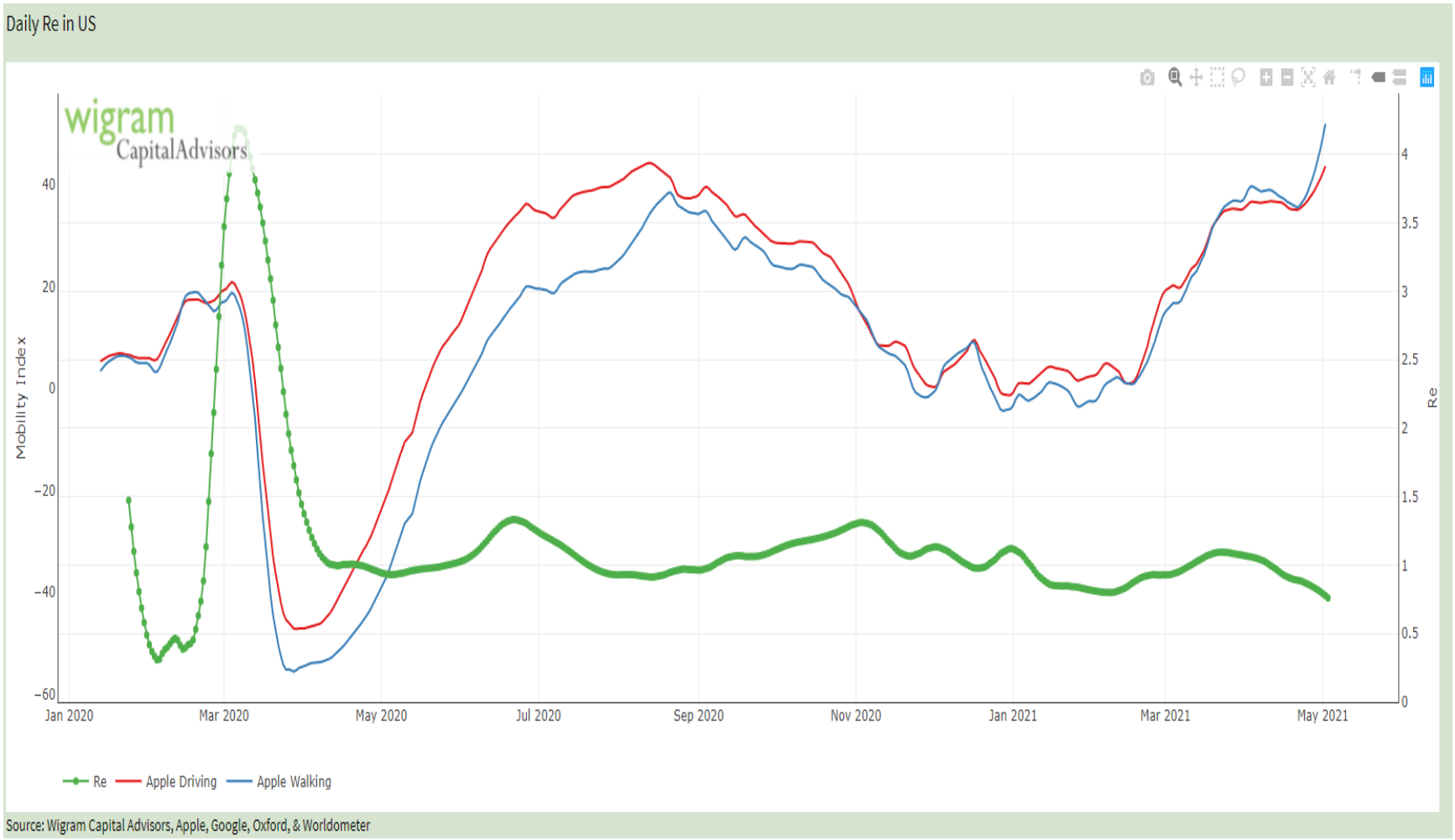
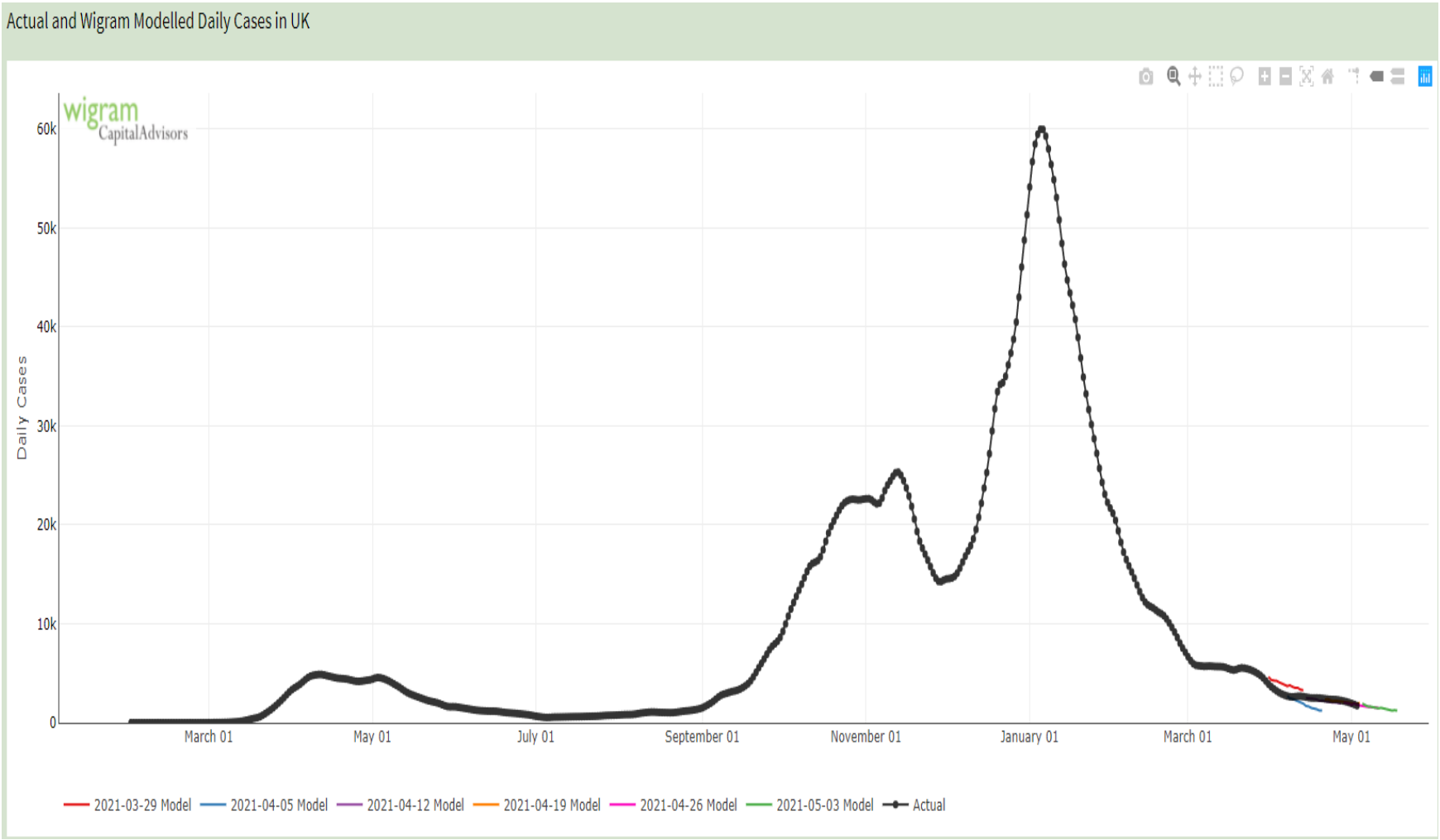
The US

While mobility is now above pre-covid levels.



The UK

The story is similar in the UK.



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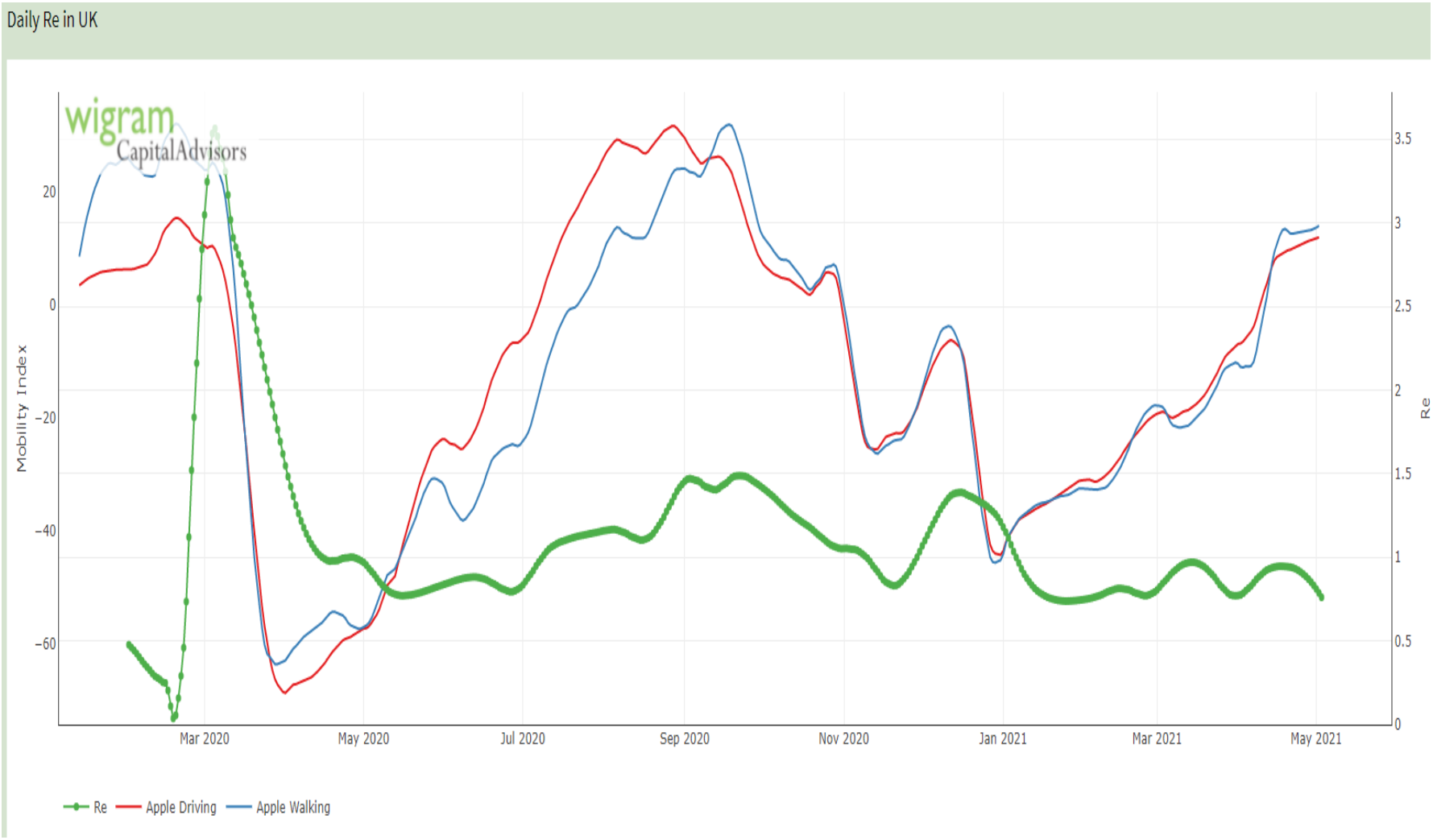
The UK – mobility and Re



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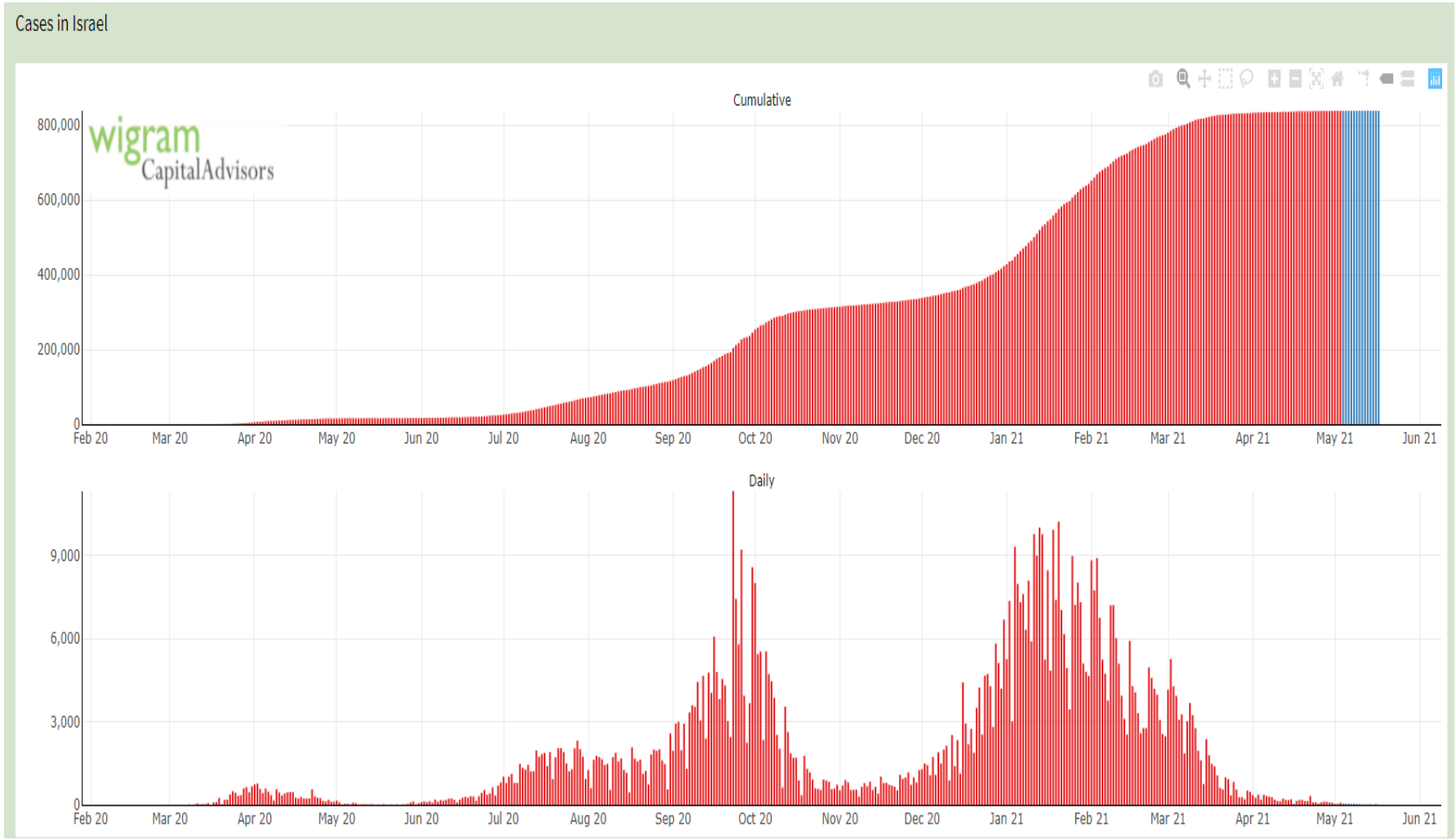
Israel

Covid cases are now tracking in the double digits.



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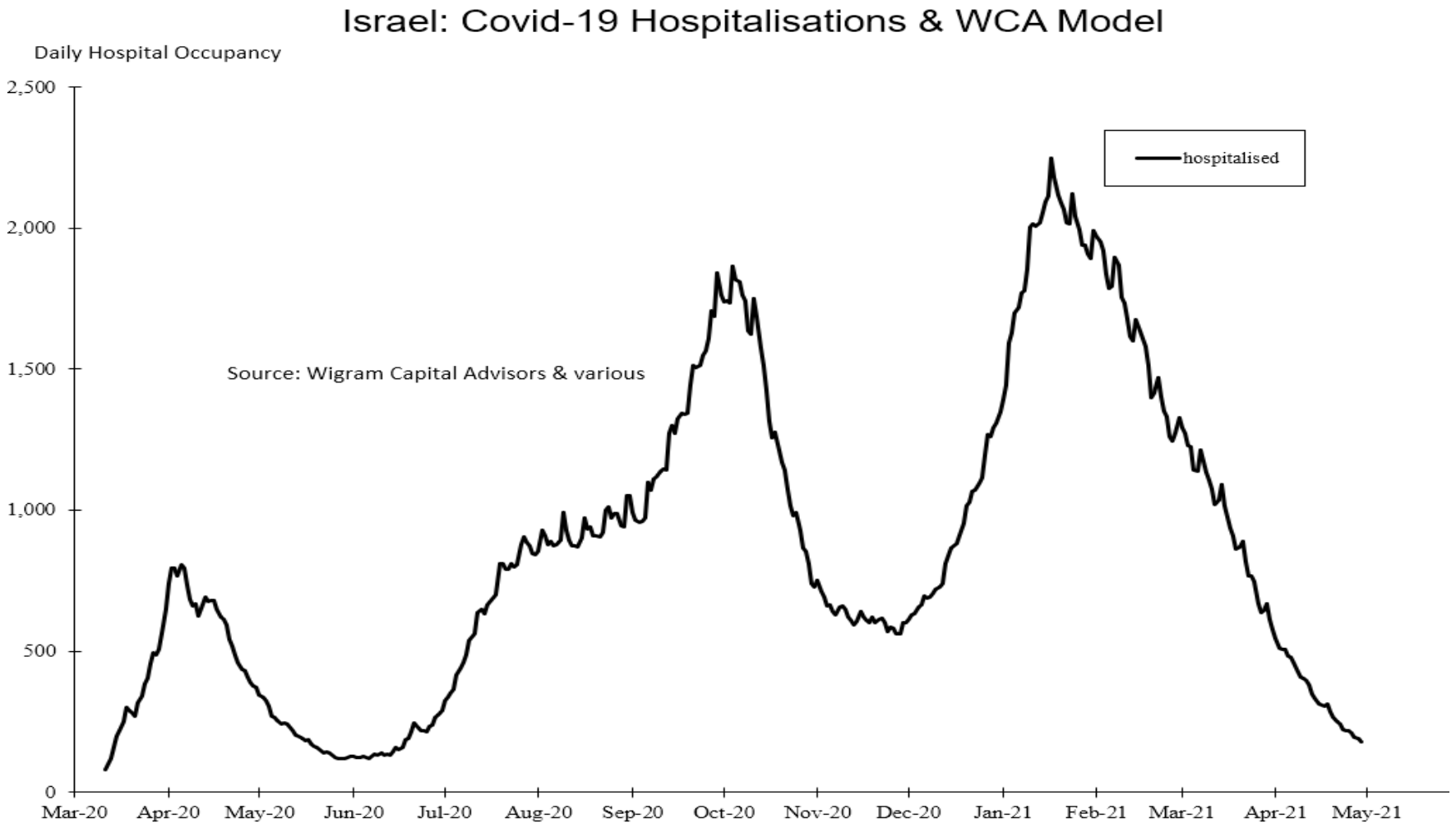
Israel

Less than 200 people in Israel are in hospital due to covid.



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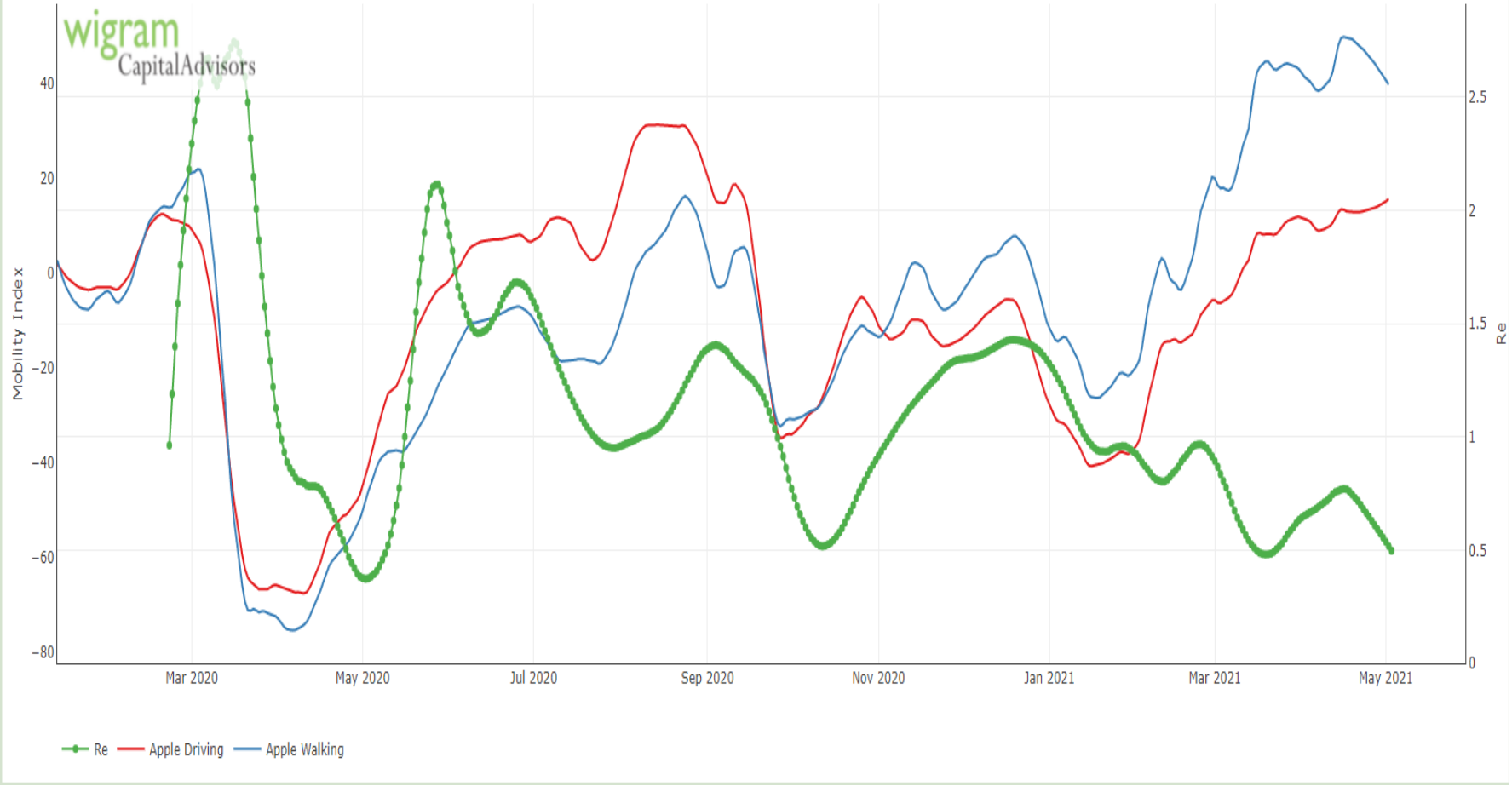
Israel – mobility and Re

Daily Re in Israel



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Israel – on track for single cases

	Actual				Model		Model	
					3-May-21	Daily change	2-May-21	Daily change
	Israel	R0 Daily	5-day avera	Daily change				
20-Apr-21	837,357	0.76	0.79	139				
21-Apr-21	837,492	0.71	0.77	135				
22-Apr-21	837,807	0.67	0.75	315				
23-Apr-21	837,892	0.63	0.71	85				
24-Apr-21	837,974	0.59	0.67	82				
25-Apr-21	838,024	0.60	0.64	50				
26-Apr-21	838,107	0.60	0.62	83				
27-Apr-21	838,217	0.60	0.60	110				
28-Apr-21	838,323	0.58	0.59	106				
29-Apr-21	838,407	0.55	0.59	84				
30-Apr-21	838,481	0.52	0.57	74				
1-May-21	838,517	0.51	0.55	36				
2-May-21	838,554	0.52	0.54	37				
3-May-21	838,621	0.59	0.54	67			838613	59
4-May-21					838671	50	838672	59
5-May-21					838716	45	838711	39
6-May-21					838761	45	838758	47
7-May-21					838796	35	838788	30
8-May-21					838836	40	838822	34
9-May-21					838868	32	838848	26
10-May-21					838896	28	838875	27
11-May-21					838914	18	838903	28
12-May-21					838935	21	838928	25
13-May-21					838958	23	838947	19
14-May-21					838983	25	838967	20
15-May-21					839001	18	838977	10
16-May-21					839031	30	838984	7
17-May-21					839044	13	839001	17
18-May-21					839061	17	839016	15
19-May-21					839071	10	839021	5
20-May-21					839081	10	839025	4
21-May-21					839090	9	839037	12
22-May-21					839098	8	839047	10
23-May-21					839105	7	839053	6
24-May-21					839112	7	839057	4
25-May-21					839119	7	839065	8
26-May-21					839131	12	839069	4
27-May-21					839138	7	839070	1
28-May-21					839144	6	839078	8
29-May-21					839152	8	839083	5
30-May-21					839157	5	839085	2
31-May-21					839162	5	839087	2
1-Jun-21					839166	4	839087	0
2-Jun-21					839168	2		

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UK – set to fall below 1,000

	Actual				Model		Model	
					03-May-21	Daily change	02-May-21	Daily change
	UK	R0 daily	5-day average	Daily change				
07-Apr-21	4,359,288	0.86	0.82	2758				
08-Apr-21	4,362,311	0.88	0.84	3023				
09-Apr-21	4,365,456	0.89	0.86	3145				
10-Apr-21	4,368,045	0.91	0.88	2589				
11-Apr-21	4,369,775	0.92	0.89	1730				
12-Apr-21	4,373,343	0.93	0.91	3568				
13-Apr-21	4,375,814	0.94	0.92	2471				
14-Apr-21	4,378,305	0.93	0.93	2491				
15-Apr-21	4,380,976	0.94	0.93	2671				
16-Apr-21	4,383,732	0.94	0.94	2756				
17-Apr-21	4,385,938	0.95	0.94	2206				
18-Apr-21	4,387,820	0.95	0.94	1882				
19-Apr-21	4,390,783	0.95	0.95	2963				
20-Apr-21	4,393,307	0.95	0.95	2524				
21-Apr-21	4,395,703	0.93	0.95	2396				
22-Apr-21	4,398,431	0.92	0.94	2728				
23-Apr-21	4,401,109	0.92	0.93	2678				
24-Apr-21	4,403,170	0.91	0.93	2061				
25-Apr-21	4,404,882	0.91	0.92	1712				
26-Apr-21	4,406,946	0.92	0.92	2064				
27-Apr-21	4,409,631	0.92	0.92	2685				
28-Apr-21	4,411,797	0.9	0.91	2166				
29-Apr-21	4,414,242	0.87	0.90	2445				
30-Apr-21	4,416,623	0.84	0.89	2381				
01-May-21	4,418,530	0.8	0.87	1907				
02-May-21	4,420,201	0.76	0.83	1671				
03-May-21	4,421,850	0.75	0.80	1649			4422274	2,073
04-May-21					4423720	1,870	4424277	2,003
05-May-21					4425659	1,939	4426191	1,914
06-May-21					4427471	1,812	4428088	1,897
07-May-21					4429121	1,650	4429904	1,816
08-May-21					4430751	1,630	4431634	1,730
09-May-21					4432313	1,562	4433415	1,781
10-May-21					4433896	1,583	4435168	1,753
11-May-21					4435360	1,464	4436884	1,716
12-May-21					4436867	1,507	4438524	1,640
13-May-21					4438285	1,418	4440157	1,633
14-May-21					4439695	1,410	4441729	1,572
15-May-21					4441011	1,316	4443244	1,515
16-May-21					4442248	1,237	4444764	1,520
17-May-21					4443517	1,269	4446269	1,505
18-May-21					4444748	1,231	4447651	1,382
19-May-21					4445983	1,235	4449044	1,393
20-May-21					4447167	1,184	4450417	1,373
21-May-21					4448218	1,051	4451747	1,330
22-May-21					4449313	1,095	4453035	1,288
23-May-21					4450412	1,099	4454351	1,316
24-May-21					4451450	1,038	4455558	1,207
25-May-21					4452442	992	4456773	1,215
26-May-21					4453390	948	4457947	1,174
27-May-21					4454284	894	4459146	1,199
28-May-21					4455204	920	4460328	1,182
29-May-21					4456055	851	4461404	1,076
30-May-21					4456883	828	4462540	1,136
31-May-21					4457698	815	4463629	1,089
01-Jun-21					4458505	807	4464697	1,068

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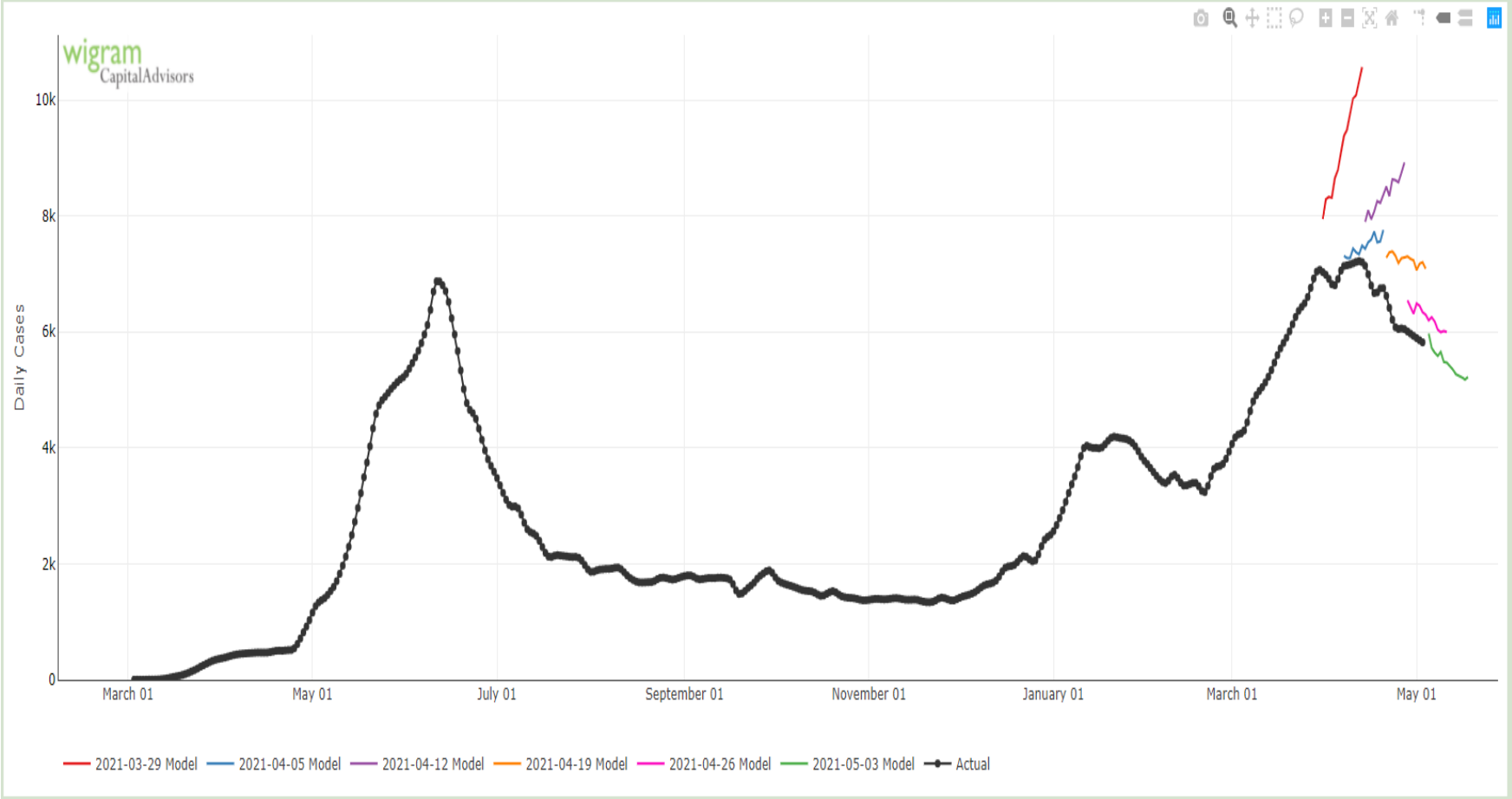
Chile

Actual and Wigram Modelled Daily Cases in Chile



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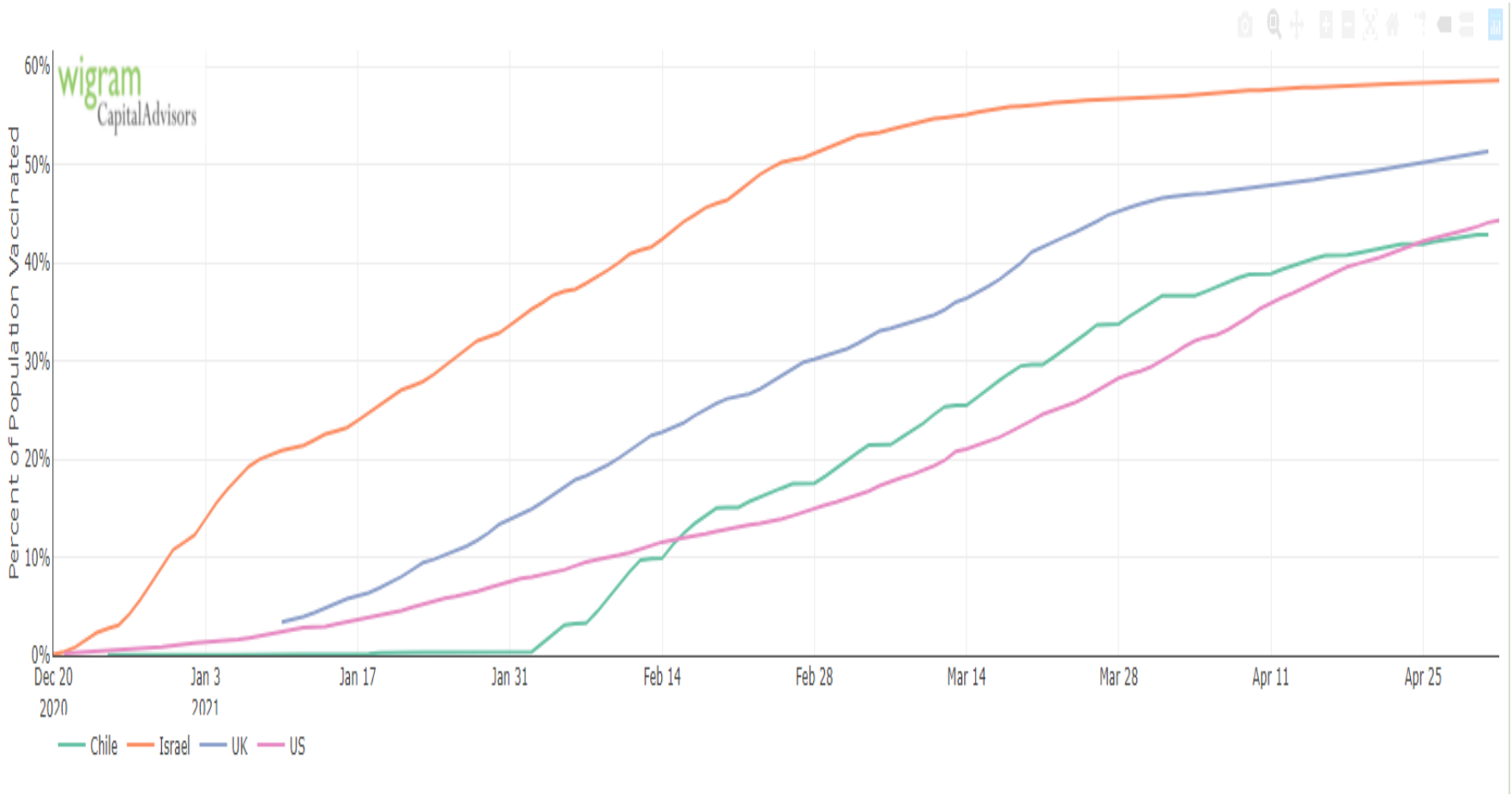
Chile – 35% have received 2nd dose of Sinovac



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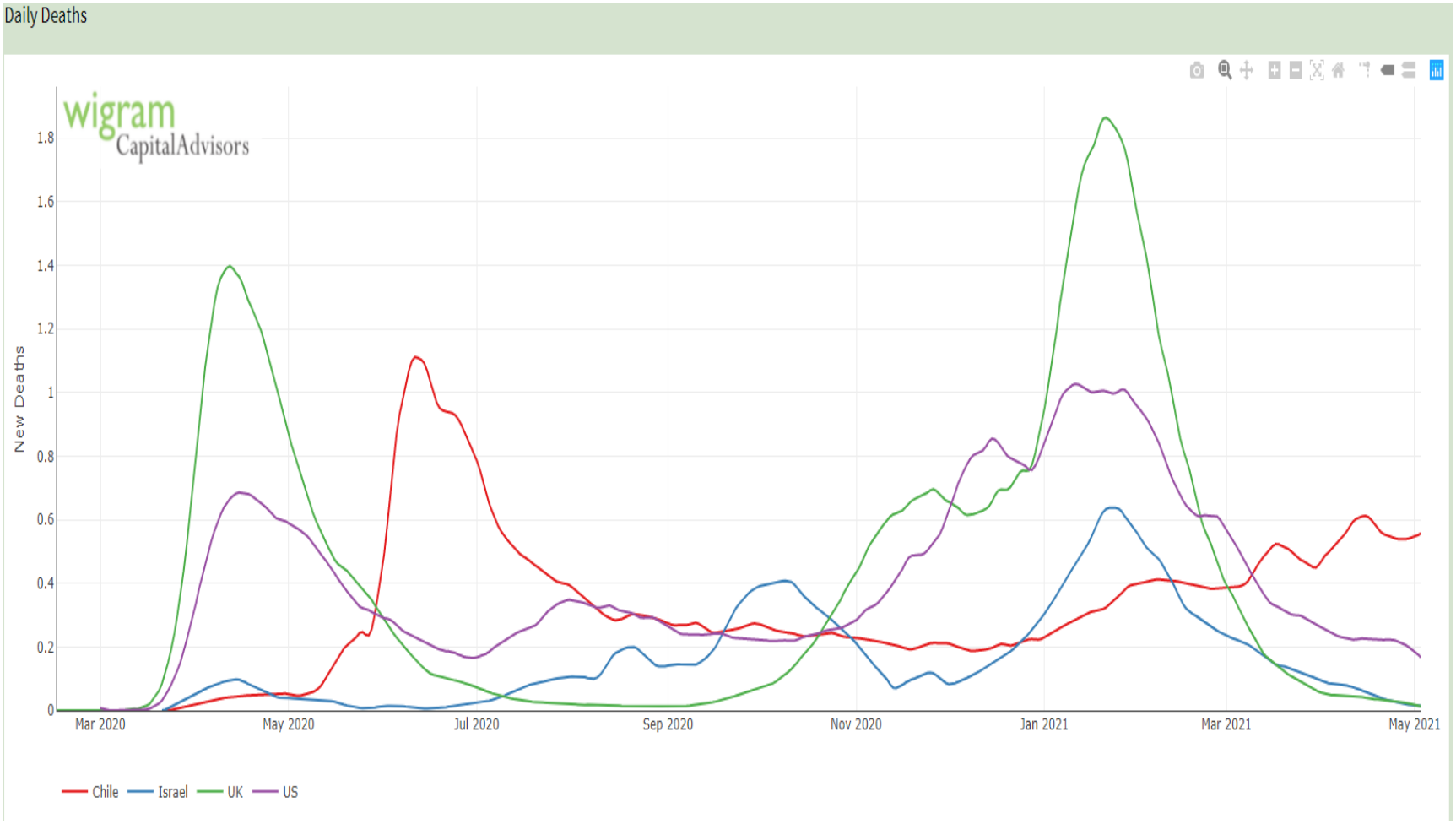
Chile – Yet deaths are elevated



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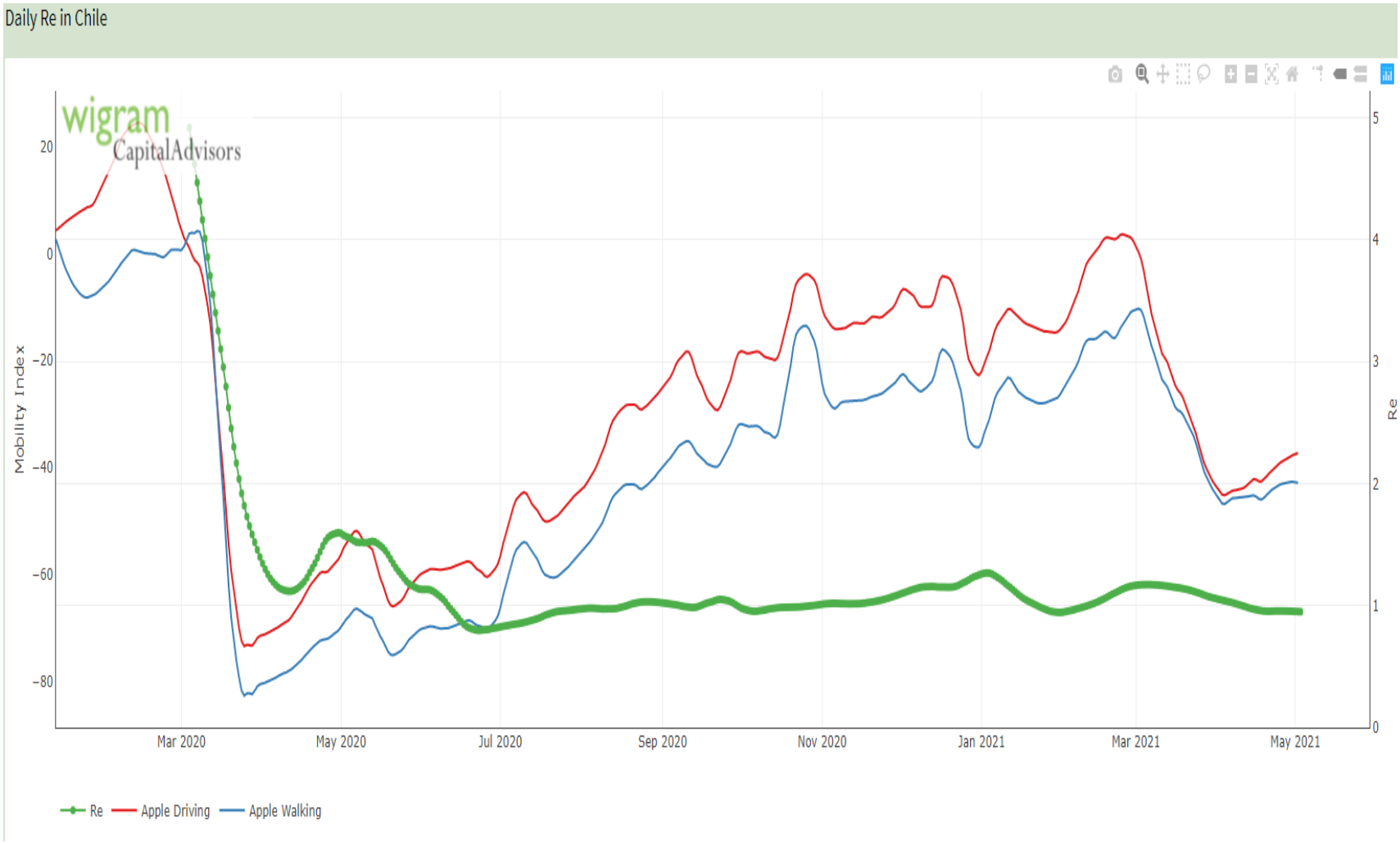
Chile – The decline in cases reflects lower mobility



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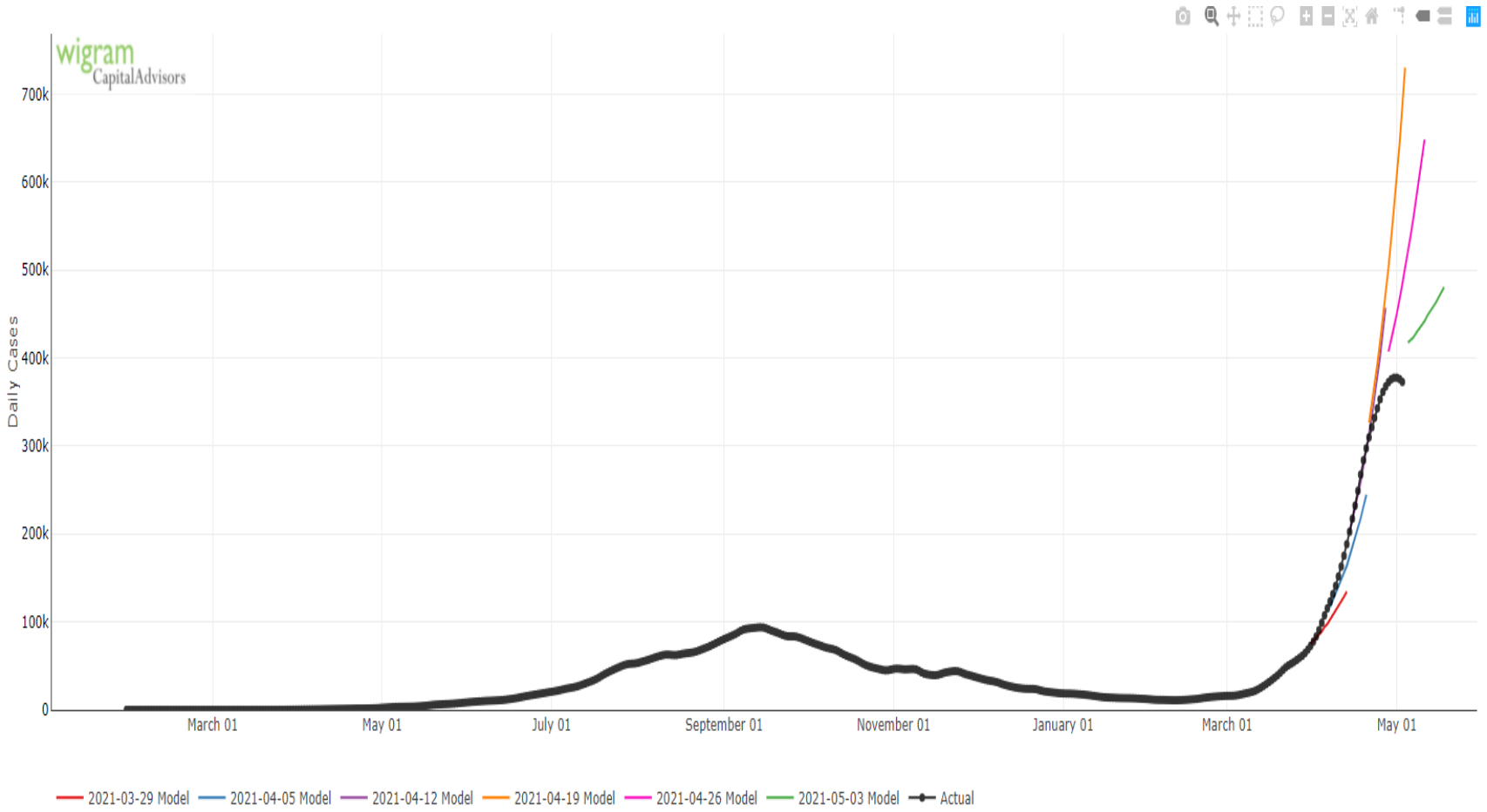
India – The curve is starting to slowly bend



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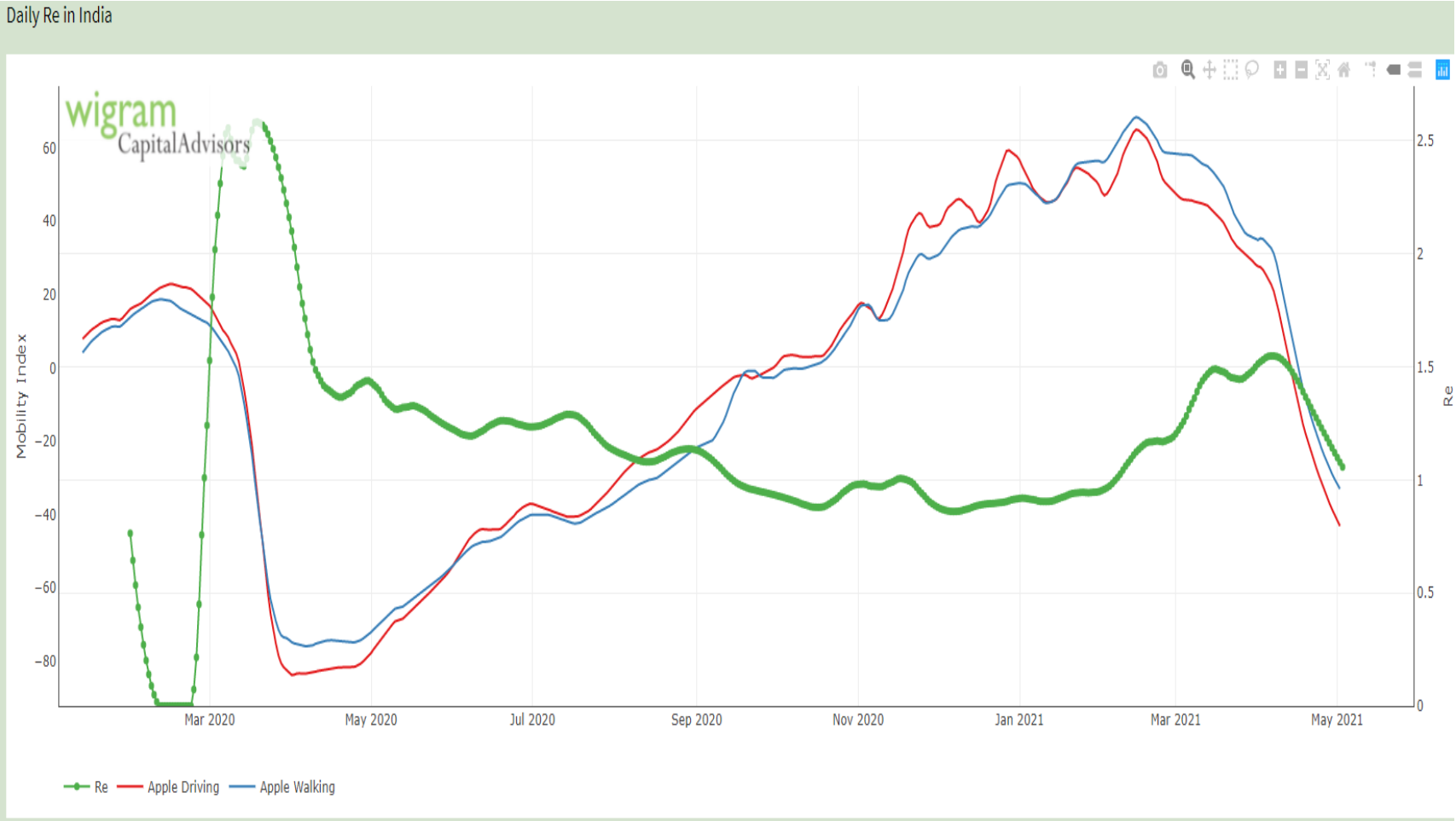
India – Mobility has finally moved



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India – The curve in Maharashtra is bending

	Actual				Model	
					3-May-21	Daily change
	Maharashtra	R0 Daily	5-day averag	Daily change		
20-Apr-21	3,960,359	1.03	1.06	62,097		
21-Apr-21	4,027,827	1.03	1.05	67,468		
22-Apr-21	4,094,840	1.01	1.03	67,013		
23-Apr-21	4,161,676	1.00	1.02	66,836		
24-Apr-21	4,228,836	0.99	1.01	67,160		
25-Apr-21	4,295,027	0.98	1.00	66,191		
26-Apr-21	4,343,727	0.98	0.99	48,700		
27-Apr-21	4,410,085	0.97	0.98	66,358		
28-Apr-21	4,473,394	0.97	0.98	63,309		
29-Apr-21	4,539,553	0.95	0.97	66,159		
30-Apr-21	4,602,472	0.93	0.96	62,919		
1-May-21	4,665,754	0.90	0.94	63,282		
2-May-21	4,722,401	0.87	0.92	56,647		
3-May-21	4,771,022	0.84	0.90	48,621		
4-May-21					4829114	58,092
5-May-21					4886003	56,889
6-May-21					4941682	55,679
7-May-21					4996510	54,828
8-May-21					5050328	53,818
9-May-21					5103130	52,802
10-May-21					5155024	51,894
11-May-21					5205956	50,932
12-May-21					5256327	50,371
13-May-21					5305632	49,305
14-May-21					5353643	48,011
15-May-21					5400872	47,229
16-May-21					5447569	46,697
17-May-21					5493527	45,958

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India – And in Delhi

	Actual				Model	
					03-May-21	Daily change
	Delhi	R0 Daily	5-day averag	Daily change		
16-Apr-21	803,623	1.57	1.74	19,486		
17-Apr-21	827,998	1.47	1.66	24,375		
18-Apr-21	853,460	1.38	1.57	25,462		
19-Apr-21	877,146	1.29	1.47	23,686		
20-Apr-21	905,541	1.21	1.38	28,395		
21-Apr-21	930,179	1.16	1.30	24,638		
22-Apr-21	956,348	1.11	1.23	26,169		
23-Apr-21	980,679	1.07	1.17	24,331		
24-Apr-21	1,004,782	1.05	1.12	24,103		
25-Apr-21	1,027,715	1.04	1.09	22,933		
26-Apr-21	1,047,916	1.03	1.06	20,201		
27-Apr-21	1,072,065	1.02	1.04	24,149		
28-Apr-21	1,098,051	1.01	1.03	25,986		
29-Apr-21	1,122,286	0.99	1.02	24,235		
30-Apr-21	1,149,333	0.95	1.00	27,047		
01-May-21	1,174,552	0.91	0.98	25,219		
02-May-21	1,194,946	0.86	0.94	20,394		
03-May-21	1,212,989	0.80	0.90	18,043		
04-May-21					1236232	23243
05-May-21					1258854	22622
06-May-21					1281070	22216
07-May-21					1303129	22059
08-May-21					1324730	21601
09-May-21					1345879	21149
10-May-21					1366688	20809
11-May-21					1387303	20615
12-May-21					1407582	20279
13-May-21					1427223	19641
14-May-21					1447102	19879
15-May-21					1466805	19703
16-May-21					1486222	19417
17-May-21					1505071	18849
18-May-21					1523696	18625
19-May-21					1542243	18547
20-May-21					1560091	17848

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MIQ – Without India, cases are lower than forecast

<5	5 to 14	15 to 24	>=25	Total_MIQ	Total_MIQ_	Date	Total_MIQ
1.06E-13	4.12E-05	0.051275	0.948684	>=25	>=25	27/12/2020	31
6.96E-17	1.85E-06	0.017434	0.982564	>=25	>=25	03/01/2021	58
1.72E-13	0.000705	0.241682	0.757612	>=25	>=25	10/01/2021	23
1.37E-08	0.057224	0.753349	0.189427	15 to 24	15 to 24	17/01/2021	15
2.28E-06	0.221139	0.673581	0.105277	15 to 24	15 to 24	24/01/2021	14
0.000257	0.586589	0.391545	0.021608	5 to 14	5 to 14	31/01/2021	11
0.001412	0.680012	0.294822	0.023755	5 to 14	5 to 14	07/02/2021	14
0.006774	0.57331	0.356932	0.062985	15 to 24	5 to 14	14/02/2021	3
0.017	0.529261	0.335108	0.118631	5 to 14	5 to 14	21/02/2021	14
0.044987	0.627733	0.262513	0.064767	15 to 24	5 to 14	28/02/2021	21
0.086446	0.536453	0.252993	0.124108	15 to 24	5 to 14	07/03/2021	23
0.072525	0.325851	0.233113	0.368511	15 to 24	>=25	14/03/2021	21
0.037722	0.073859	0.085669	0.802751	>=25	>=25	21/03/2021	30
0.07711	0.075023	0.055908	0.791959	>=25	>=25	28/03/2021	25
0.038247	0.01404	0.012852	0.934861	>=25	>=25	04/04/2021	26
0.088481	0.041186	0.017955	0.852378	>=25	>=25	11/04/2021	45
0.108025	0.055551	0.016966	0.819458	15 to 24	>=25	18/04/2021	20
0.324056	0.20117	0.028954	0.44582	5 to 14	>=25	25/04/2021	9

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MIQ – India risk has peaked

0 to 1	2 to 4	5 to 10	>10	IN_MIQ_f	IN_MIQ_f	Date
0.39912	0.395617	0.160923	0.04434	2 to 4	0 to 1	07/06/2020
0.409797	0.362629	0.162035	0.065539	0 to 1	0 to 1	29/11/2020
0.345645	0.459444	0.137336	0.057575	0 to 1	2 to 4	06/12/2020
0.306394	0.512926	0.127422	0.053258	2 to 4	2 to 4	13/12/2020
0.402071	0.378508	0.165446	0.053976	2 to 4	0 to 1	20/12/2020
0.402392	0.384977	0.164242	0.048388	>10	0 to 1	27/12/2020
0.372599	0.424	0.153804	0.049597	0 to 1	2 to 4	03/01/2021
0.339756	0.466061	0.141384	0.052799	5 to 10	2 to 4	10/01/2021
0.328386	0.48285	0.138581	0.050183	2 to 4	2 to 4	17/01/2021
0.338431	0.473445	0.141655	0.046468	5 to 10	2 to 4	24/01/2021
0.357406	0.454841	0.145626	0.042127	2 to 4	2 to 4	31/01/2021
0.415108	0.387662	0.160211	0.037019	0 to 1	0 to 1	07/02/2021
0.572509	0.139595	0.23971	0.048186	5 to 10	0 to 1	14/02/2021
0.577572	0.035694	0.29869	0.088045	0 to 1	0 to 1	21/02/2021
0.567967	0.027816	0.298682	0.105536	5 to 10	0 to 1	28/02/2021
0.476785	0.001419	0.371055	0.150741	0 to 1	0 to 1	07/03/2021
0.290378	1.11E-05	0.428906	0.280705	>10	5 to 10	14/03/2021
0.104765	8.96E-09	0.280412	0.614824	>10	>10	21/03/2021
0.051322	1.31E-10	0.16758	0.781098	5 to 10	>10	28/03/2021
0.016877	2.72E-13	0.061379	0.921744	>10	>10	04/04/2021
0.051427	3.64E-11	0.051655	0.896918	>10	>10	11/04/2021
0.097139	5.45E-10	0.042126	0.860735	>10	>10	18/04/2021
0.21944	4.51E-08	0.048419	0.732141	5 to 10	>10	25/04/2021
0.327803	7.24E-07	0.057663	0.614533		>10	02/05/2021
0.339905	1.12E-06	0.064038	0.596056		>10	09/05/2021
0.367517	2.47E-06	0.072345	0.560135		>10	16/05/2021
0.392794	5.07E-06	0.080481	0.52672		>10	23/05/2021
0.414948	9.51E-06	0.08808	0.496962		>10	30/05/2021

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MIQ – UK is at 0-1

0 to 1	2 to 3	4 to 7	>=8	UK_MIQ_f	UK_MIQ_f	Date
0.001569	0.347624	0.602159	0.048648	4 to 7	4 to 7	13/12/2020
7.63E-06	0.155001	0.734687	0.110304	4 to 7	4 to 7	20/12/2020
3.13E-07	0.086248	0.665694	0.248057	2 to 3	4 to 7	27/12/2020
2.1E-07	0.033556	0.123001	0.843442	>=8	>=8	03/01/2021
0.00016	0.031625	0.012462	0.955753	>=8	>=8	10/01/2021
0.051882	0.137853	0.025437	0.784828	>=8	>=8	17/01/2021
0.308074	0.218192	0.040439	0.433295	0 to 1	>=8	24/01/2021
0.510032	0.257914	0.067311	0.164742	2 to 3	0 to 1	31/01/2021
0.553931	0.267591	0.085683	0.092795	2 to 3	0 to 1	07/02/2021
0.578865	0.268633	0.102189	0.050313	2 to 3	0 to 1	14/02/2021
0.686261	0.205027	0.075011	0.0337	0 to 1	0 to 1	21/02/2021
0.705879	0.194838	0.075606	0.023677	0 to 1	0 to 1	28/02/2021
0.715546	0.192857	0.079562	0.012035	0 to 1	0 to 1	07/03/2021
0.717168	0.192731	0.079594	0.010507	0 to 1	0 to 1	14/03/2021
0.742399	0.175134	0.071394	0.011073	2 to 3	0 to 1	21/03/2021
0.774597	0.15074	0.060739	0.013924	0 to 1	0 to 1	28/03/2021
0.792256	0.140552	0.057487	0.009706	0 to 1	0 to 1	04/04/2021
0.808326	0.132959	0.05261	0.006106	0 to 1	0 to 1	11/04/2021
0.81538	0.128825	0.050411	0.005384	2 to 3	0 to 1	18/04/2021
0.819675	0.125585	0.049316	0.005424	0 to 1	0 to 1	25/04/2021
0.865085	0.094041	0.037287	0.003586		0 to 1	02/05/2021
0.867724	0.092434	0.036413	0.003429		0 to 1	09/05/2021
0.868369	0.091999	0.036234	0.003398		0 to 1	16/05/2021
0.868912	0.091633	0.036082	0.003373		0 to 1	23/05/2021
0.869251	0.091405	0.035988	0.003357		0 to 1	30/05/2021

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MIQ – US is at 0-1

0 to 1	2 to 4	5 to 10	US_MIQ_f	US_MIQ_f	Date
0.00238	0.271631	0.725989	5 to 10	5 to 10	13/12/2020
0.003197	0.403361	0.593442	5 to 10	5 to 10	20/12/2020
0.016551	0.5716	0.411848	2 to 4	2 to 4	27/12/2020
0.001479	0.165588	0.832933	2 to 4	5 to 10	03/01/2021
0.000638	0.277478	0.721884	5 to 10	5 to 10	10/01/2021
0.00474	0.72155	0.27371	2 to 4	2 to 4	17/01/2021
0.03161	0.903368	0.065022	2 to 4	2 to 4	24/01/2021
0.06919	0.905491	0.025319	2 to 4	2 to 4	31/01/2021
0.198108	0.793991	0.007901	2 to 4	2 to 4	07/02/2021
0.377304	0.619631	0.003065	2 to 4	2 to 4	14/02/2021
0.644136	0.355275	0.000589	0 to 1	0 to 1	21/02/2021
0.636418	0.362957	0.000626	0 to 1	0 to 1	28/02/2021
0.733611	0.266126	0.000263	2 to 4	0 to 1	07/03/2021
0.799271	0.200613	0.000116	2 to 4	0 to 1	14/03/2021
0.809786	0.190116	9.81E-05	0 to 1	0 to 1	21/03/2021
0.759687	0.24012	0.000193	2 to 4	0 to 1	28/03/2021
0.718713	0.280982	0.000305	0 to 1	0 to 1	04/04/2021
0.675787	0.323761	0.000452	0 to 1	0 to 1	11/04/2021
0.617505	0.38177	0.000725	0 to 1	0 to 1	18/04/2021
0.593638	0.405499	0.000863	0 to 1	0 to 1	25/04/2021
0.924932	0.075041	2.75E-05		0 to 1	02/05/2021
0.929578	0.070399	2.3E-05		0 to 1	09/05/2021
0.931906	0.068073	2.16E-05		0 to 1	16/05/2021
0.933631	0.066348	2.05E-05		0 to 1	23/05/2021
0.93484	0.065141	1.98E-05		0 to 1	30/05/2021

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DEPARTMENT OF THE PRIME MINISTER AND CABINET
TE TARI O TE PIRIMIA ME TE KOMITI MATUA

Vaccines Modelling

Overview of modelling and preliminary results at 3 May 2021.
This pack predominantly relates to modelling undertaken by Te Pūnaha Matatini under the direction of Shaun Hendy.
Work is ongoing.

Modelling can help us understand the future dynamics of the COVID-19 system

Our vaccination programme will influence the outcomes that the Elimination Strategy seeks to achieve:

We care about:

- **Whether outbreaks occur** when new cases are seeded into the community, **how easy such outbreaks are to detect**, and **how big they are when detected;**
- How **effective our control measures are** in responding to outbreaks (Alert Levels, contact tracing and case management, etc); and
- **What the impacts of these outbreaks are** in terms of health-related harms and deaths.

Domestic vaccination will influence these by:

- **Reducing the chances of a new outbreak** being caused by each seed case;
- **Reducing the rate of transmission** for outbreaks in vaccinated populations, by reducing susceptibility to infection and/or reducing infectiousness of those carrying the disease; and
- **Reducing the impacts** of being infected amongst those who are vaccinated.

Questions that modelling can help answer

1. At different stages of the vaccination campaign:
   a) **How does the relationship between cases and harms change?** As the most-at-risk populations get vaccinated earlier, we would expect a change in relationship.
      - *What might we expect a case fatality rate to be at different stages of the vaccine rollout?*
      - *What are the outcomes associated with realistic/plausible end-states for the immunisation programme?*

   b) **What is the reduction in the R value we might expect at different stages of vaccine rollout?**
      - *When do we not need higher Alert Levels to control potential outbreaks (ie using contact tracing/testing alone)?*
      - *When might outbreaks begin to require little control (ie, not even Alert Levels)?*
      - *When, and how, might the Alert Levels need to change (ie which environments restrictions are applied to)?*

2. **How should vaccinations be sequenced in order to optimise the transmission or harm reduction achieved?**
      - *While many sequencing decisions have been taken, there may be tactical choices for government to make later in the year: where is the best return on investment likely to be if we are seeking to drive engagement and uptake higher?*

3. **What are the risks and benefits of different options and approaches, at different times, as we look to future decisions to safely reconnect New Zealanders with the world.**
      - *Can we predict and monitor the risk of infectious arrivals at the border? [NB: Not a modelling question, but an analytical one]*
      - *Can we define and calibrate a "risk budget" that will allow us to accept some international travellers without requiring an MIQ stay on arrival (ie, as is suggested for Phase 3)? Are there other ways to manage Phase 3?*
      - *What are the possible timeframes associated with these Phases?*

Glossary (selected terms)

Reproduction number: The average number of secondary infections arising from each case.

R_0 is the baseline/reference value, R_{eff} is the "effectiveness reproduction number" given controls, etc, and R_v is the reproduction number resulting in a partially vaccinated population.

Vaccine effectiveness: $e_T = [\text{xx}]\% -$ effectiveness at preventing transmission

$e_D = [\text{xx}]\% -$ effectiveness at preventing severe disease

Non-Pharmaceutical Interventions (NPIs) are interventions to manage the spread of COVID-19, such as Alert Level Restrictions, intensive contact tracing and isolation of cases, etc.

Herd Immunity

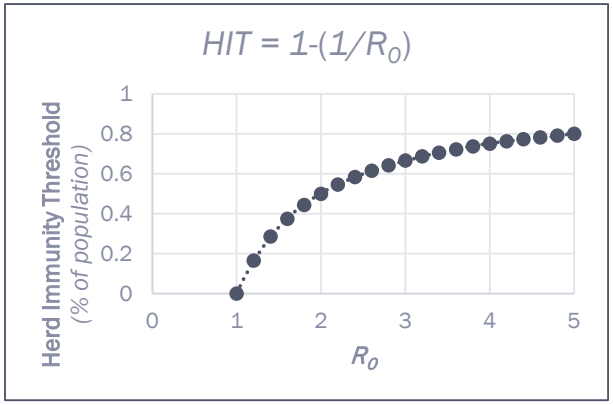
"Herd immunity" is a continuous quantity, and refers to the indirect protection that is gained when a sufficient percentage of the population has become immune to infection.

The "Herd Immunity Threshold" is where there is "so much herd immunity" that transmission cant occur in a sustained way, or where $R_{eff} = 1$.

Mathematically, HIT = $1-(1/R_0)$ - and so this is dependent on your estimate for R_0 (right).

However, herd immunity gains are continuous: we will see reduced transmission (R_{eff}) in outbreaks of a partially vaccinated population.

NB: R_0 is a function of behaviours and interventions, too.



NB: The maths is an average, and we are interested in achieving herd immunity effects in sub-populations, too. Indeed, we are likely *more interested* in results in certain populations.

Two models have been used by TPM researchers

A deterministic SEIR "compartment" model.

This model assumes a static level of vaccination at the beginning of a period, and then runs for 2 years with frequent infected people entering the community and no mitigation. It looks at the number of people in the population who would get infected, hospitalised, etc.

The stochastic "branching process" model.

This model simulates the impact of a single case entering a population with a particular proportion of people vaccinated. It provides a distribution of outbreak sizes (numbers of active cases) at the point of detection. It allows for discussion and comparison of different management strategies for dealing with cases.

TPM also own **a "contagion network" model,** but this has not been applied to these questions at this stage. There are plans for future work using this model.

Other researchers (eg ESR) have been doing immunisation related modelling, too.

The modelling relies on some critical assumptions

Some of these are uncertain or situational, either intrinsically (eg on R_0), or because of the stage of the vaccine rollout we are currently at (eg on uptake rates). ***Key assumptions include:***

Variable	Notes
The estimated reproduction number, R0.	The central scenario used for the modelling assumes an R_0 of 2.5. Outcomes are very sensitive to this choice.
Vaccine take-up rate.	The central scenario assumes 90% uptake. At this stage, sensitivity of different vaccine take-up rates have not been included but we know that different take-up rates will be a key driver of outcomes we could experience.
Distribution of vaccine take-up by location or ethnic group.	This has not yet been explored in the analysis. We anticipate "homophily" (the tendency of individuals to associate with similar others) will be an increasingly important factor as population-wide coverage increases, and R reduces. In this context, this means that if unvaccinated individuals are more likely to interact with one another, we would expect any outbreaks will be increasingly likely to occur in communities where this is more common. We will be able to observe overall and sub-population take-up as the vaccination programme gathers pace.
Assumptions on vaccine effectiveness in terms of prevention of severe disease and prevention of reduction in transmissibility.	The results suggest that modelling choices for these variables have greater effects at higher vaccine roll-out points. Refining our view on vaccine effectiveness is therefore likely to be important later in the year, once a significant portion of the population is vaccinated – but is less relevant earlier in the year.
Homogeneous mixing assumptions.	The sensitivity analysis shows these assumptions can make a significant difference to the results.
Age-based susceptibility, for instance on whether children are less susceptible to infection.	This relates to the value of possible control measures which target particular environments (such as schools) and how long different control measures might need to remain in the non-pharmaceutical intervention (NPI) "toolkit".

While many of these assumptions are unknown or inherently uncertain, the modelling helps us conceptualise different plausible futures, and understand how the outcomes we care about are sensitive to changes in these key variables.

The focus in interpretation should be on comparisons between scenarios rather than specific point estimates. The broad shape and feel of the results is unlikely to change, even if some of the specific values do. These results are shared now to support understanding about how domestic vaccination will influence COVID-19 management strategy.

DEPARTMENT OF THE PRIME MINISTER AND CABINET
TE TARI O TE PIRIMIA ME TE KOMITI MATUA

Discussion of results

Interpretation provided by the Modelling Steering Group (officials of MOH, DPMC, Treasury, MBIE, MSD, StatsNZ) in collaboration with the lead researchers.

Discussion: Herd immunity and vaccination coverage *(1/2)*

Results discussed on this slide come from the deterministic SEIR compartment model.

Many of the scenarios modelled will not eventuate in reality, such as any which suggest a large set of impacts which arise from unmitigated spread. In reality, NPIs will continue to be applied if case numbers increase, mitigating further spread. Such results, therefore, indicate the value associated with maintaining elimination, but should not be taken as articulation of a plausible scenario.

Key insights:

1. **The modelling suggests that "herd immunity" will require very high levels of uptake**, probably including vaccination of children. The breadth and consistency of vaccination coverage achieved is more important than how quickly we get there.

2. **At 90% of over 15year olds vaccinated, we will continue to need NPIs to prevent large outbreaks.** This may include Alert Level 3 type controls in some situations.

3. **In very optimistic scenarios, with high uptake and effectiveness, there would be no self-sustaining epidemics even without NPIs** - but we would still expect small numbers of cases and fatalities: a step change to the status quo (Table 1). Herd immunity is not sufficient to completely avoid outbreaks.

4. **In a scenario where take-up or effectiveness is not sufficient to create herd immunity**, an alternative choice for decision-makers would be around whether there are realistic NPIs which could reduce R_{eff} to a level where self-sustaining epidemics become implausible.

Discussion: Herd immunity and vaccination coverage *(2/2)*

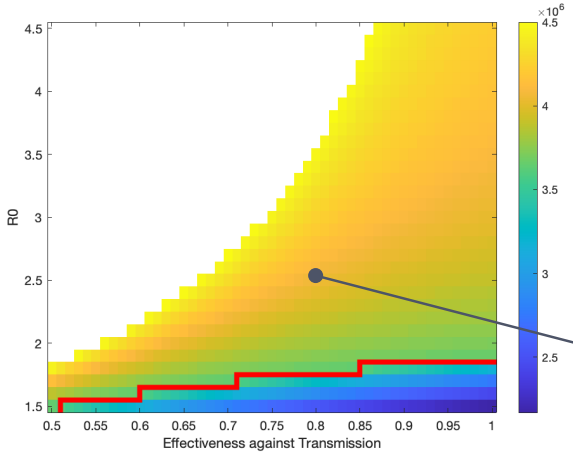


Figure 4. Number of vaccinated individuals required for $R_v = 1$ at varying R_0 and e_T values. *Squares below the red-line are scenarios that do not require vaccination of under 15-year-olds. White squares represent scenarios where $R_v = 1$ is unobtainable without additional reduction in R (or greater than 90% coverage).*

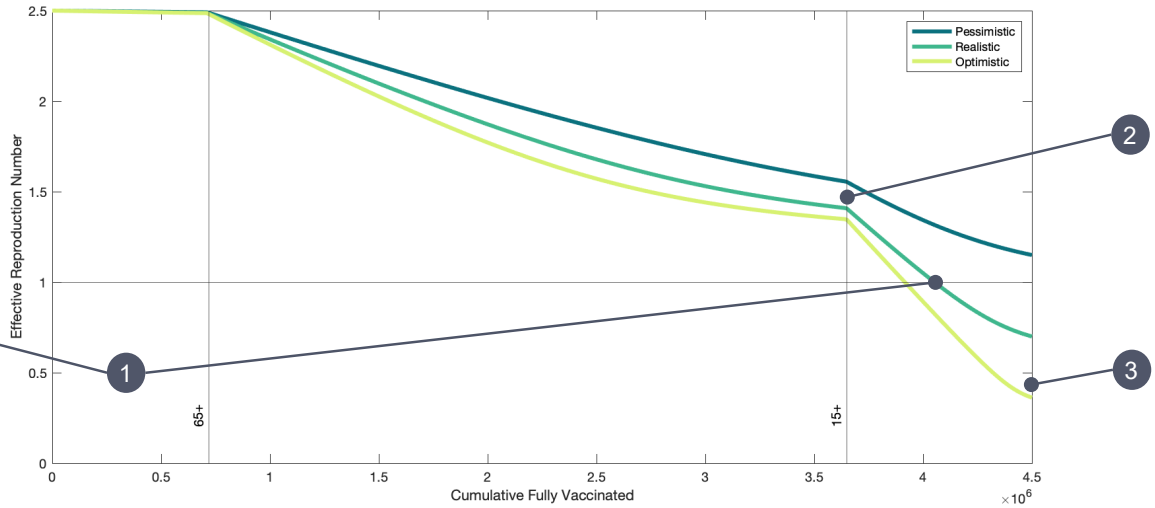


Figure 2. Effective reproduction number after vaccination as a function of total vaccine courses administered. *The programme is assumed to begin with the 65+ age-groups, then the 15-64 year-old age-groups, and finally the 0-14 year-old age-groups, with at most 90% of any group vaccinated.*

4

Table 1	Optimistic
Vaccine Effectiveness	$e_T = 95\%, e_D = 98\%$
Coverage	90% (inc. children)
R_v	0.4
Symptomatic cases	910
Hospitalisations	54
Fatalities	6

Discussion: Impacts and vaccination coverage *(1/2)*

Results discussed on this slide come from the deterministic SEIR compartment model.

These charts (next page) demonstrate what the previous results might mean in terms of outbreak size, hospitalisations and fatalities.

Broadly speaking, the results are that fatalities (3) should decrease more quickly than hospitalisations (2), and, in turn, hospitalisations should decrease more quickly than cases (1).

These are expected results, given the choices made in the model structure to vaccinate from the oldest age groups down. This broadly reflects the nature of the government's vaccine sequencing choices.

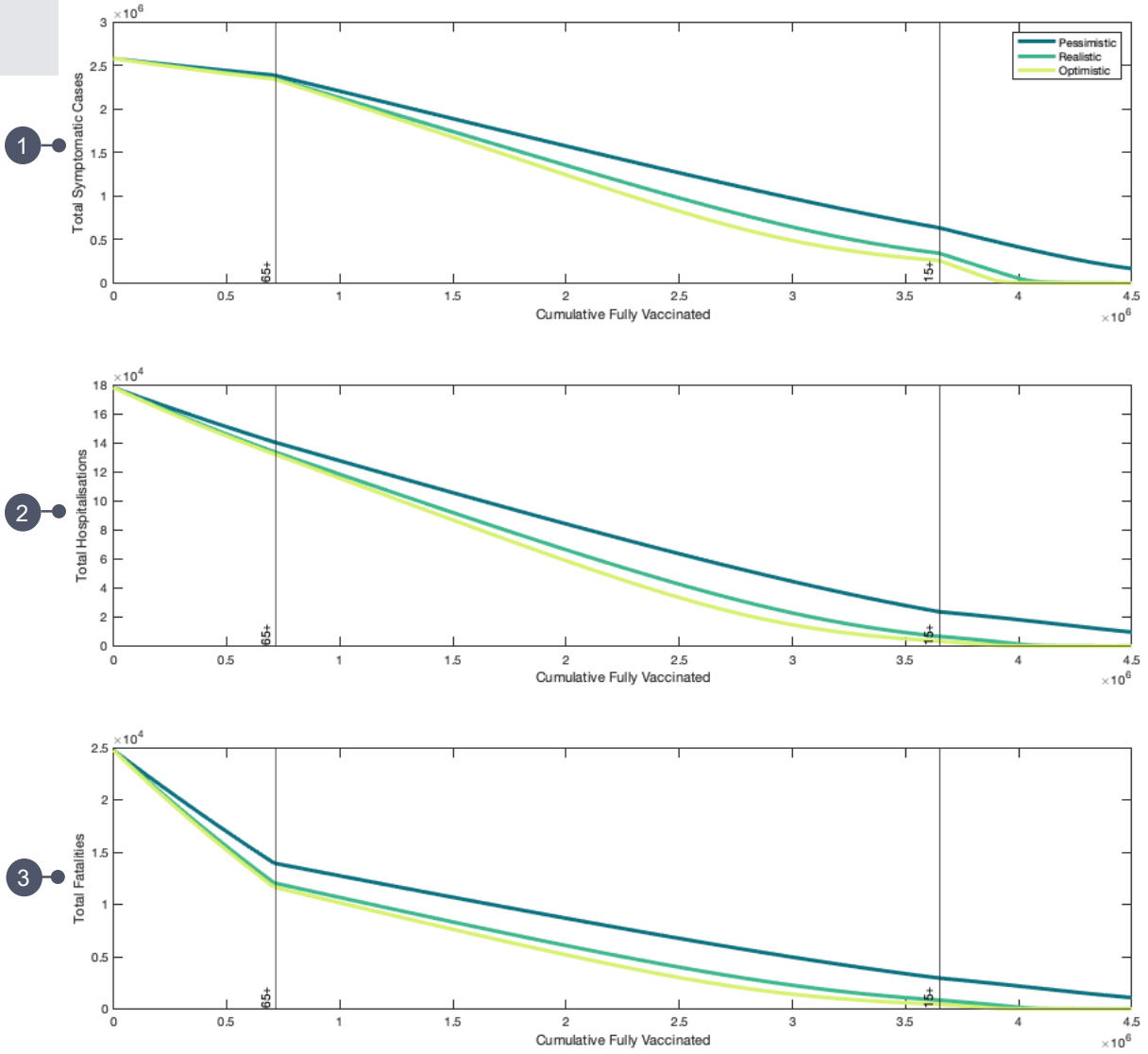
Please note the different scales on the charts. The total symptomatic cases (over a 2 year simulation, at 0% vaccinated, with no mitigations) are modelled at around 2,500,000 people. At the corresponding points, the total hospitalisations are modelled at around 180,000 people and the total fatalities are around 25,000 people.

Discussion: Impacts and vaccination coverage *(2/2)*

Figure 3. Total local symptomatic cases (top), hospitalisations (mid), and fatalities (bottom) *over a 2-year period for given vaccination levels and 5 imported cases per day.*

Up to 90% of any age-group is vaccinated, beginning with older groups, before successively moving through younger groups.

Only local cases are included in the charts (ie not the flow of cases which are assumed to be imported).



Discussion: Mitigating outbreaks

These results are from the stochastic "branching process" model, which simulates the impact of a single case entering a population with a particular proportion of people vaccinated. It provides a distribution of outbreak sizes (numbers of active cases) at the point of detection.

This allows us to look beyond the "unmitigated spread" outcomes. While the pre-detection spread is always unmitigated, post-detection government and citizens have choices about how to respond and change behaviours.

We would expect our control measures to become more efficient as vaccination rates increase.

In particular:

1. The **expected size of outbreaks would be smaller (at detection, and by elimination),** as the effective reproduction number (R_{eff}) reduces;
2. **Control measures do not have to be as effective to drive $R_{eff} < 1$** (ie to drive elimination); and
3. Combining these features, **controls required to achieve elimination would not be required for as long.**

These results needs to be balanced against the possibility for increased frequency of these (smaller) outbreaks which might be associated with more open borders. A large enough number of events may offset the potential benefits, relative to the status quo.

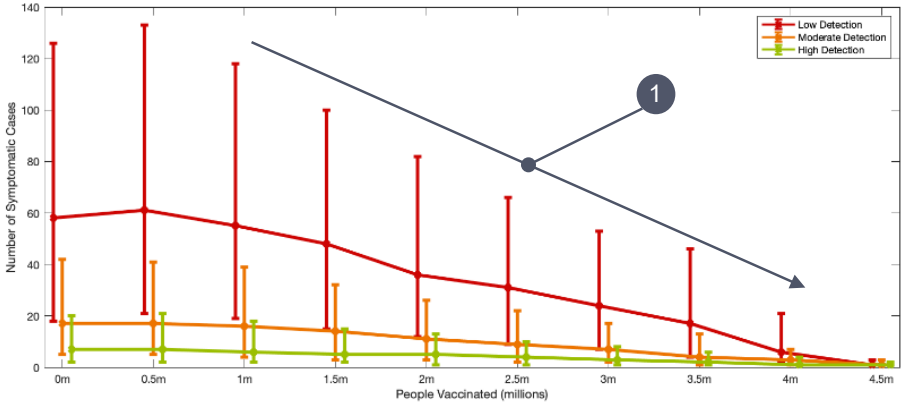
Discussion: Mitigating outbreaks

Red, Orange and Green relate to
Low, Medium and High detection (testing) regimes.

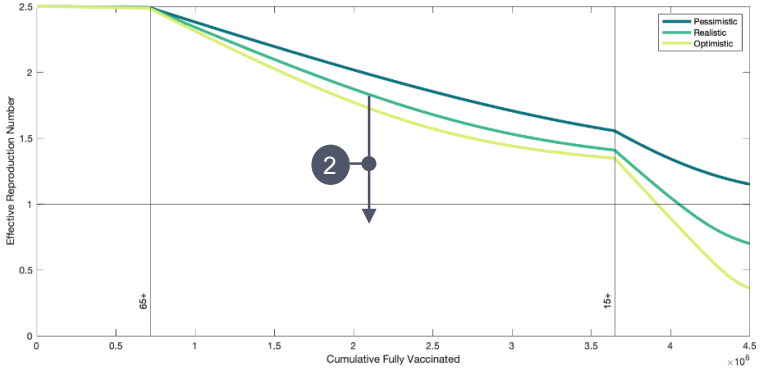
Low detection assumes a symptomatic individual in the community has a 5% of being detected.
Moderate detection assumes 15%.
High detection assumes 30%.

The results show that until high levels of vaccination are achieved, testing rates are more important in determining the size of outbreaks at detection (than vaccination).

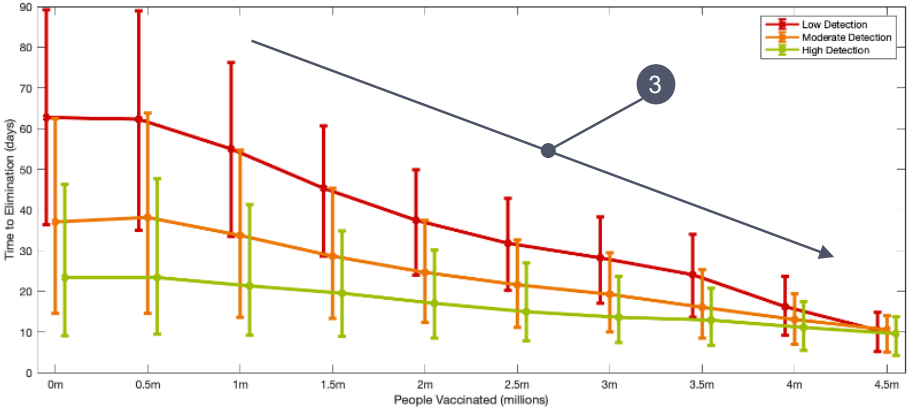
Total cases at detection vs people vaccinated



Decreasing R_{eff} vs people vaccinated



Time to elimination vs people vaccinated

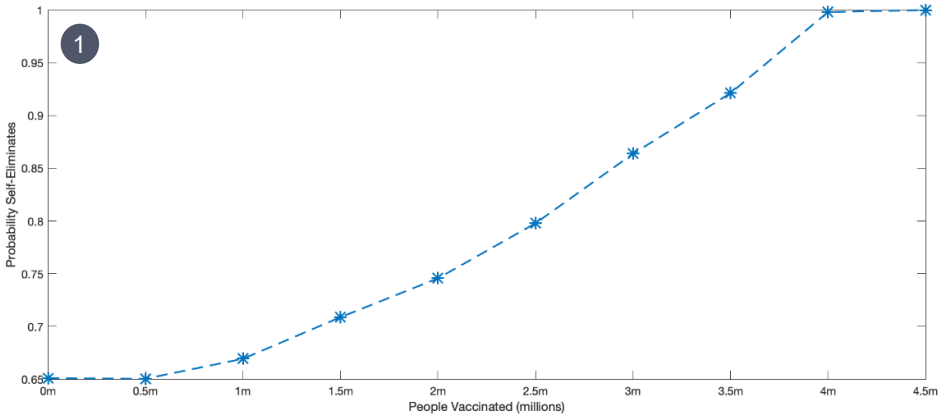


Discussion: "Budgeting" risk

The modelling could inform how we think about the potential risks being taken with different border options.

- As herd immunity is not sufficient to completely avoid outbreaks, the rate of reintroduction of infections across the border is likely to remain relevant, in 2 ways:
  1. The likelihood of outbreaks from each seed case will reduce; and
  2. The expected number of cases arising from each outbreak would reduce.

1



2

As a rule-of-thumb, for any $R < 1$, the expected number of cases caused by a single re-introduction is given by $\frac{R}{1-R}$. If $R = 0.95$, this means there will be an average of 19 community cases for every border re-introduction.

- Achieving vaccination coverage well beyond the herd immunity threshold will reduce the likelihood and severity of these outbreaks.

- The overseas context will therefore become less important as domestic vaccination rates increase, but it will remain an important factor, nevertheless. It is likely to be important that we integrate our understanding on country/traveller risk, outbreak risk/severity/frequency, and expected control measures required at different points in time, in order to navigate the next 2+ years.

Variants and modelling

The possibility of new variants interacts with the modelling results in a couple of ways.

The first is that **new variants may be more transmissible or cause more severe disease**. This changes the dynamics of the system, because R_0 is a critical assumption.

- We are doing sensitivity analysis on R_0 values used in the modelling, which can be used as a proxy for more transmissible variants.
- We could do something similar to account for more severe disease, too, but given the goals of the Elimination Strategy, this is less important to our strategy.

The second is that **vaccines already administered could have reduced effectiveness** against new variants, weakening the "immunity state" of the population.

- As above, sensitivity analyses on the assumptions for vaccine efficacy against transmission and severe disease will allow us to explore the impacts of such variants on a partially vaccinated population.

Next steps for the TPM modelling work

Officials and TPM are discussing next steps across three themes:

1. Expanding the results to cover a broader range of plausible scenarios, including a wider range of values for key variables (ie those on slide 6).

2. Producing different cuts of the existing analysis to more easily inform different policy questions: refining our understanding of the impacts of different control measures, or finer granularity in numbers of imported cases to simulate different risk appetites, and overlaying intelligence from the immunisation programme in order to add a time component (analysis currently relates primarily to coverage, free of time).

3. Identifying new modelling questions that may require more significant input or work, including use of the contagion network model and specific assessment regarding differentials in uptake across different communities.

We recognise that it is important to communicate results carefully, and with appropriate caveats. Officials and TPM are working to refine presentation of results, thinking about different audiences – particularly decision-makers, the academic community and the public.

Additionally:

- **We are seeking to engage with Sir David Skegg's SC19PHAG on this material.**
- **TPM looking to publish these results towards end of May.**

Questions

Any questions or comments on content, or on next steps?

How and when should we share this material with Ministers?

What are your thoughts on the publication of the underlying model results, and managing or responding to the public debate?

ESR paper on Vaccination Strategies

ESR have produced a paper called "COVID-19 Age-related Vaccine Strategies for Aotearoa New Zealand".

Table 1 outlines the headline results from the report, relating to various "vaccine scenarios".

- e_d relates to vaccine effectiveness at preventing severe disease
- e_t relates to vaccine effectiveness at preventing transmission

NB: This paper is currently undergoing formal peer review and is pre-publication. We would need to check before using these results further at this stage.

Table 1: Comparison of cases, hospitalisations, and deaths in New Zealand population – 10 imported cases per day with open borders or 7,300 total imported cases

Vaccine scenarios (e_d/e_t effectiveness & uptake)	Vaccine strategies	Peak active cases	Total community cases	Peak hosps.	Total hosps.	Total deaths
95/70% uniform 80% coverage	minimise R_{eff}	**591**	**38,300**	32	2,460	475
	high-risk	626	41,300	**27**	**2,050**	**323**
95/60% uniform 80% coverage	minimise R_{eff}	**1,690**	**121,000**	64	4,380	882
	high-risk	1,960	139,000	**54**	**3,700**	**590**
95/40% uniform 80% coverage	minimise R_{eff}	**50,500**	**1,460,000**	995	25,000	4,900
	high-risk	54,000	1,520,000	**909**	**22,100**	**3,700**
70/60% uniform 80% coverage	minimise R_{eff}	**22,500**	**916,000**	**1,300**	47,700	8,960
	high-risk	25,300	981,000	1,360	**47,200**	**8,280**
95/40% & 70/60% uniform 80% coverage	dual vaccines	25,800	1,030,000	790	27,700	3,550

ESR paper on Vaccination Strategies

- These (hard to interpret) graphics relate to similar variables as the TPM material.
- Figure 2, below, shows herd immunity thresholds under permutations of effectiveness (disease, transmission) and uptake ("coverage"). General result is the intuitive one, that more effectiveness relates to lower coverage, and vice versa.
- Figure 3, across, shows how herd immunity is and isn't achievable in 4 different vaccine scenarios, given different levels of coverage within age groups (y-axis), and across the whole population (x-axis).

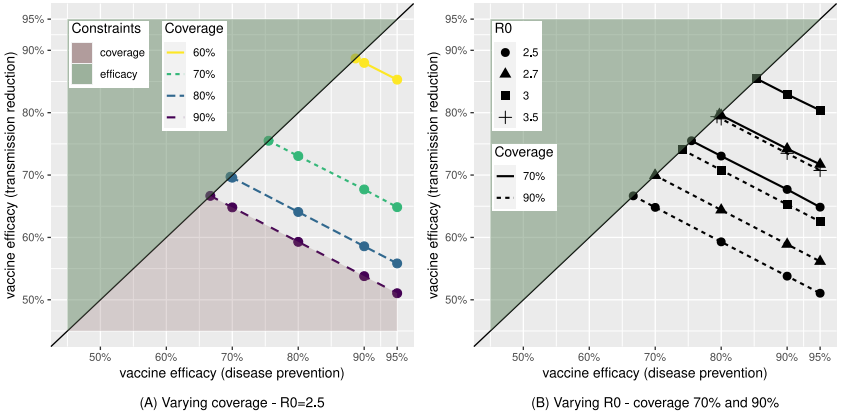


Figure 2: Vaccine effectiveness and New Zealand population vaccine uptake requirements for herd immunity.

NB: The minimal vaccine effectiveness on transmission reduction and disease prevention for herd immunity at multiple vaccine uptake levels given a fixed R_0=2·5 (A) and at different R_0 values given uptake levels of 70% and 90% NZ population (B). Both effects are considered equal across age groups in this analysis. As the vaccine effectiveness on transmission reduction is expected to be not greater than the vaccine effectiveness on disease prevention, all herd immunity lines are limited to the bottom half of the plot (divided by the black line).

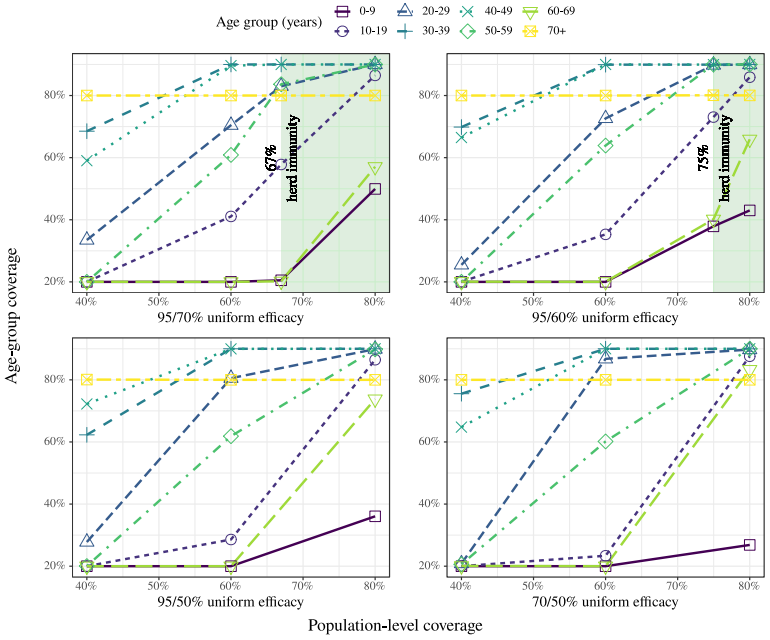


Figure 3: Age-group allocations of vaccine strategy 1 at various VE scenarios.

NB: Vaccine allocations of the spread-minimising strategy (strategy 1) at fixed uptake levels and minimal uptake level required for herd immunity (border lines of the green areas). A vaccine has two values of effectiveness: disease prevention and transmission reduction. The basic reproduction number R_0 is 2·5. The effectiveness of a vaccine is called "uniform" if their effectiveness is equal across age groups.

Example: modelling to create interactive tools

Graph below shows vaccination states combined with testing protocols, and the impact on effective transmission. The dashed line is notional herd immunity threshold Reff =1, and more blue = less transmission.
Source: https://twitter.com/CT_Bergstrom/status/1380158598639190021

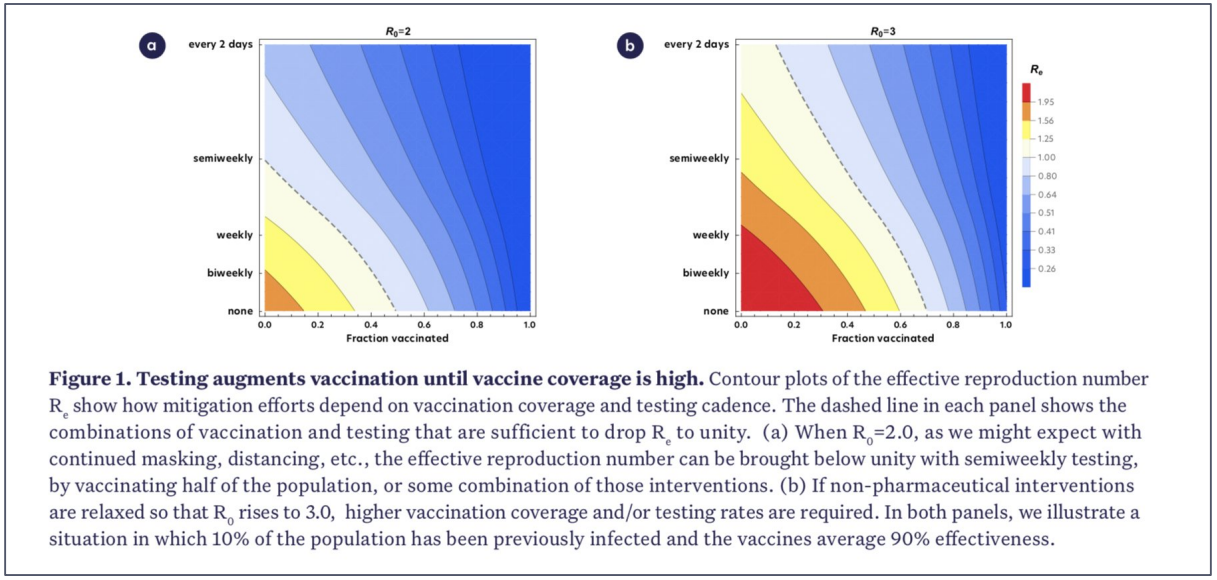
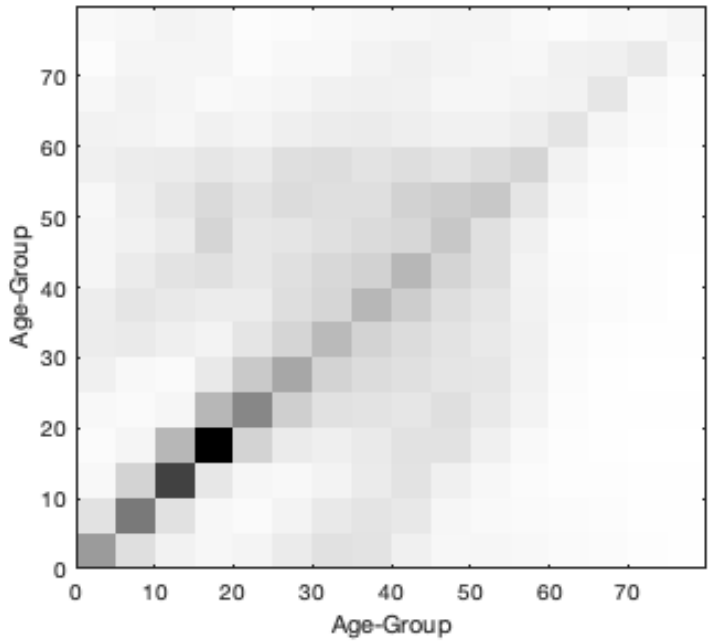


Figure 1. Testing augments vaccination until vaccine coverage is high. Contour plots of the effective reproduction number R_e show how mitigation efforts depend on vaccination coverage and testing cadence. The dashed line in each panel shows the combinations of vaccination and testing that are sufficient to drop R_e to unity. (a) When R_0=2.0, as we might expect with continued masking, distancing, etc., the effective reproduction number can be brought below unity with semiweekly testing, by vaccinating half of the population, or some combination of those interventions. (b) If non-pharmaceutical interventions are relaxed so that R_0 rises to 3.0, higher vaccination coverage and/or testing rates are required. In both panels, we illustrate a situation in which 10% of the population has been previously infected and the vaccines average 90% effectiveness.

The academics have created an interactive tool: https://www.color.com/testing-and-vaccines-model
Could do the same for different control measures (eg contact tracing, alert levels, etc)

Contact matrix used in the model



Darker colours indicate more contacts.

C_{ij} represents the number of contacts that an individual in group *i* has with individuals in group *j*.

In this visualisation, *i* denotes the i^{th} row from the bottom, and *j* the j^{th} column from the left.

Officials commissioned a TPM report on vaccines and modelling, per the schema below

Overall objective: Minimise harmful effects from COVID-19 in border opening scenarios			
(1) For a given vaccine scenario…	(1) …when we vary our approach to managing the borders…	(1) ….what is the impact on re-incursion risk…	(1) … and what are the consequences for community transmission?
Key staging points: Proportion of population (group) vaccinated: 10%, 50%, 80% (to be adjusted for uptake – see cell below) These points are based on rough estimates of % of age groups eligible at different stages of rollout: • At the end of Tier 2 vaccination approx. 20% of over 65 year olds and 12% of under 65 year olds will have been offered vaccination; overall ~11%. NB the over 65s here include many ARC residents who will not be mixing much in the community. • At the end of Tier 3 vaccination all over 65 year olds and approx. 35-50% of under 65 year olds will have been offered vaccination; overall between 40 to a bit over 50%. • At the end of the initial rollout of the vaccination programme all people aged over 16 (~80% of the population) will have been offered vaccine. **Efficacy**: 95% efficacy for second dose for preventing symptomatic infection. This is based on Pfizer vaccine 2 doses 3 weeks apart. For asymptomatic infection: 50%, 75% and 85% efficacy which match TPM's border worker scenario paper, plus a more optimistic view.	Focus on three scenarios: (a) Highest risk scenario: Full reopening without restrictions (a) Lowest risk scenario: Re-open without restriction to only vaccinated travellers, 14 day MIQ for others. (a) Medium risk scenario: Vaccinated travellers enter without restrictions, non-vaccinated travellers to self-isolate for 7 days Need to test each scenario against each vaccine efficacy assumption	• What is the estimated number of re-incursions per month for each of these scenarios? • What is the distribution of sizes of incursions at detection? (including those that remain undetected, where size at detection is effectively 0).	• What is the likely number of community cases these re-incursions would then cause? • For subsequent [outside of the model] analysis we then want to understand the potential impact of these cases (e.g. deaths, number of hospitalisations, number of mild cases) • How quickly would each Alert Level (2-4) contain the spread? • What is the impact on groups that would face higher risk (e.g. elderly, comorbidities)?
Notes/points for discussion			
• Using uptake of influenza vaccination as recorded on the national immunisation register as a proxy for likely uptake of COVID vaccine for over 65-year-olds, gives us: ○ 59% for Māori, 73% for Pacific, 52% for Asian, and 70% for other; 67% overall.. These figures are a known underestimate (not all flu vaccinations make it onto the NIR), but provide a 'pessimistic scenario'. We might also want to model an optimistic (say) 90% uptake. • For the population under 65, suggest modelling a range similar to the above – i.e. 70% and 90%. • Possibly also consider use of assortativity to mimic heterogeneity in uptake.	For arriving traveller risk: • Assume a baseline of current observed prevalence of infection detected in MIQ: 183/24999 arrivals in January and February tested positive at some stage during MIQ. • Use current prevalence of infection in non-Australians in MIQ for prevalence in arrivals, assume no cases from Australia (to simulate impact of QFTZ with Australia) • Use current prevalence of infection in non-Australians in MIQ for prevalence in arrivals, plus a seed case directly into the community (to simulate impact of QFTZ with Australia but a case from Australia entering NZ) • Use half current prevalence of infection detected in MIQ, to simulate reduction in infection due to vaccination in source countries.	A graph for each scenario showing the distribution of the size of outbreak at detection against the number of simulations with that outcome would be useful. We are wanting to look at results per 10,000 travellers rather than having to tie to actual estimated volumes. We are trying to find out how many new 'seed cases' we'll experience through the border. May need to frame the question differently.	Can we assess the effects in selected areas/regions? For example South Auckland or Northland to assess the impacts on different demographic (age and ethnicity) profiles? Consider varying R(eff), based on previous analyses, to capture the effect of potential changes in Alert Levels (and thereby the use of NPIs – distancing, masks etc).
Other factors to consider			
Testing tactics: • Baseline - Weekly NPS • Weekly NPS, saliva test in between • Twice-weekly saliva only	Community testing: • Baseline: Current (prevaccination) symptomatic testing levels by age, ethnic group, region (where available/model can include) • Vary the % of symptomatic people testing, given the proportion vaccinated. For example, assume ¼ or ½ the rate of symptomatic testing among vaccinated people and use % vaccinated to calculate an overall % tested.		

Further detail on next steps (1)

Presentation of a "realistic scenario range"

We would like to understand the amount of effort that would need to go into doing this, as we don't want to get in the way of more important work. It isn't a must have but it would be helpful.

The main reason for requesting this is to try to focus attention on the broad range of outcomes that we might reasonably expect based on what we currently know. It would help to draw attention away from individual point estimates.

This will potentially become more important as we grapple with and have to advise on some of the more detailed questions set out further below.

While the various sensitivities and scenarios in the paper provide us with outputs that enable us to do this already, it would be helpful to have this provided as a standard output "range" in the results.

To do this we suggest using the existing realistic scenario as a starting point, but with the following adjustments:

- Using R3.0 and R3.5 as two alternative variables
- Using a 90% vaccine take-up rate (but also as a nice to have also using a 85% take up rate)
- Keeping the realistic vaccine effectiveness assumptions, but also something slightly more optimistic on transmission (say 90%)?
- All other assumptions stay the same as now.

We would then be able to present a range of indicative outcomes associated with the different combinations of assumptions at different staging posts.

Further detail on next steps (2)

Different cuts of analysis

Policy question	What conclusions can we draw from the work so far?	What is needed
At what point of the vaccine roll-out would it be possible to start increasing covid case numbers (to a small degree) while being able to maintain a small number of negative health outcomes (i.e. 1-10 fatalities per year)? This question is relevant to phase 3 of the proposed border opening framework that the recent DPMC/Health led policy sprint has been considering.	The results indicate that there is likely a very limited window in which a small number of cases could be let in (without alert level restrictions) while maintaining only a small number of fatalities. Even once 90% of the whole population is vaccinated with 0.5 cases per day fatalities are not entirely eliminated. Table A5 of the *"A COVID-19 Vaccination Model for Aotearoa New Zealand – Appendix"* sets out that in the pessimistic scenario at R1.1, 0.5 cases per day would lead to hundreds of fatalities. However, the results do not show outcomes for a more realistic scenario at R1.1. However, these results exclude any control measures (including isolation and contact tracing).	It would be helpful to have modelling outputs to the following: A much lower daily incursion rate (there are border opening options that would allow us to only marginally increase risk). Suggest: - 5 incursion per month - 10 incursion per month Be able to see in one table the impacts associated with these incursions at more granular vaccine roll-out points: - Staging point 3 - Then successive points from that stage until whole population vaccinated.
What impact would different control measures (excluding alert level changes) have on outcomes at higher vaccine roll-out points (I.e. between staging point 3 and 90% of whole population)? In particular we are interested in understanding this in relation to the above question (i.e. in a period where we may be trying to manage a small number of incursions, with the vaccine rolled out to a significant degree).	Table 4 in the initial paper included a table that illustrated the impact that contact tracing and isolation requirements would have on the probability of a single seed outbreak. However, we have not seen the impact of these measures at much higher vaccine roll-out points (I.e. as we are close to R1.0). We have also not seen how expected health outcomes might vary with these measures in place or not.	Can we more clearly see the impact of iscolation and contact tracing measures on the overall results in the modelling. If we were to produce a "realistic scenario range" as set out above, we might be able to see how that range would change with the control measures in place.

Further detail on next steps (3)

Further analysis

Policy question	What conclusions can we draw from the results so far?	What is needed?
What impact would lower vaccine take-up in specific locations have on outcomes/equity?	Modelling not yet done.	TPM to confirm exactly what they need from officials. Is this just an instruction on what geographical areas to use, or more? Officials need to consider approach to choosing areas, which could be based off: - Areas where we have evidence of lower existing vaccination rates. - Areas with a higher Maori population, or lower socio-economic. - Looking at both a more urban/dense, and more rural/spread out area. - The number of areas to look at (possibly 3)?
How would the distribution of outcomes look if the Maori population had a lower take-up of the vaccine overall.	Modelling not yet done.	Could we look at a scenario where Maori take up is: - 80% or 70% - While the rest of the population is at 90%
Homogeneity	Sensitivity analysis has been done, which shows a large potential impact depending on assumptions. However, we do not have a good sense of what overall conclusion we should be drawing from this. While this isn't so relevant for overall high-level messages, at this point. It does become more important as we start to consider different opening choices/points.	TPM to consider and report back on how we should best think about the results across the two matrix, and if any further development of modelling approach on here is warranted/realistic.

Key conclusions and next steps - vaccine modelling work

To: COVID-19 Modelling Governance Group
From: COVID-19 Modelling Steering Group

This note provides an overview of the approach TPM is taking to the vaccine/border opening modelling outputs, a summary of the key messages we can draw from the work, and an overview of proposed next steps.

How can the modelling results so far be used?

Important to interpret the results carefully and focus on broad patterns in results…

- Focus should be on comparisons between scenarios rather than specific point estimates.
- Can provide a very general view of the broad level of risk we might expect at different stages of the vaccine roll-out, although these are best considered as indicative and "outcome ranges" given uncertainties of the scenario we will face and the indicative nature of the modelling.

Can provide an indication of how key outcome measures will change as vaccines roll-out…

- Can provide insights on how the relationship between cases and harms change as the vaccine is rolled out.
- Can provide insights on the broad proportion of the population we will need to vaccinate in order to have confidence in "acceptable" health outcomes being met.

And can inform some of the policy questions we are interested in…

- Informing what public health measures may need to stay in place to mitigate the impact of open borders as and once the vaccine is rolled out.
- When might we not need higher Alert Levels to control outbreaks?
- Beginning to form a view of the conditions that would need to be met in order to enter phase 3 and phase 4 of the proposed border opening framework, and the possible timeframes associated with those stages.

Initial insights

Herd immunity

- **Will require vaccination of children**. Based on the realistic scenario provided in initial results the model suggests herd immunity will not be reached until at least the 10-15 year old age group have been vaccinated.
- **But we don't know how many**. We consider some of the assumptions that have gone into the realistic scenario are overly optimistic (in particular the R0 we will face) so the proportion of children who would need to be vaccinated could go below 10 year olds.

Health impacts from COVID-19 are expected even if herd immunity is reached

- **We can expect ongoing impacts even once a very high vaccination rate is reached**. Hospitalisations and fatalities are likely under all reasonable scenarios once the border opens. Even if 90% of the entire population have been vaccinated we would expect ongoing hospitalisations and fatalities.

- **And these are small but uncertain impacts**. While under the realistic scenarios considered the scale of these impacts is expected to be very small (e.g. 10 or so fatalities per year if there are five infected arrivals/day) the outcomes are still reasonably sensitive to R0 and the volume and prevalence of international arrivals.

Health impacts once vaccine rolled out to the adult population only

- **Negative health impacts are expected** if the border was reopened before children are vaccinated. In the realistic scenarios explored these are at the level of a few hundred fatalities per year.

What are the most important variables that impact on the results?

- **The most important variable is the R0 assumption**. The realistic scenario used for the modelling assumes an R0 of 2.5. The modelling suggests that an increase in the R0 assumption from 2.5 to 3.0 increases the number of fatalities by around 65% at staging point 3 (in an open border scenario). *Given the scale of sensitivity officials consider it sensible to be using a higher R0 for an realistic scenario (in order to align it with what we know about the likely dominant variant)*.

- **Vaccine effectiveness assumptions make a difference at higher vaccine roll-out points.** For example, at staging post 3 the difference between the realistic and optimistic efficacy assumptions lead to a roughly a halving of hospitalisation and fatality numbers between the two scenarios. This suggests as we learn more about vaccine efficacy (both in terms of transmission and disease severity for VoCs) we will have a better idea of the scale of risk associated with border opening at different stages.

- **Homogeneous mixing assumptions**. The sensitivity analysis shows these assumptions can make a significant difference to the results, particularly at the earlier stages of the vaccine roll-out. The homogenous mixing scenario will over-estimate the level of mixing across age groups. The standard contact model used (based on New Zealand survey data) *may* underestimate mixing, but it is not necessarily that case that outcomes for New Zealand would lie between these two assumptions (e.g. if there was significant homophily in vaccination status amongst contacts). This points to the need to think broadly about the range of possible outcomes.

- **Aged based susceptibility**. The results show that *if* we assume children are less susceptible to infection, then this would significantly reduce disease spread at staging point 3. However, there is not yet a clear scientific basis for this assumption and therefore it does not make sense to factor this impact into broad conclusions. The finding does provide some indication of the potential value of targeted protections to prevent disease spread among children (e.g. at school).

- **Vaccine take-up rate**. Sensitivity of different vaccine take-up rates have not been included in the analysis so far. However, it is possible to gain an indicative sense of the impact of a lower take-up rate at different staging points by looking the impacts at the period immediately ahead of that staging point being reached. If take-up rates were 5-10% lower than the 90% assumed in the realistic scenario, this could have a reasonably large bearing on the point at which a more open border could be moved to.

- **Distribution of vaccine take-up by location or ethnic group**. This has not yet been explored in the analysis.

Next steps

We have identified three broad areas of next steps.

The first is to do with agreeing a "realistic scenario range" that we think would be helpful in the presentation of core results from the work..

The second is to do with different cuts of the existing analysis to more easily inform different policy questions.

The third is to do with new modelling questions that require more significant input or work.

Where it makes sense we have framed these against a specific policy question we are interested in.

Presentation of a "realistic scenario range"

The main reason for requesting this is to try to focus attention on the broad range of outcomes that we might reasonably expect based on what we currently know. It would help to draw attention away from individual point estimates.

This will potentially become more important as we grapple with and have to advise on some of the more detailed questions set out further below.

While the various sensitivities and scenarios in the paper provide us with outputs that enable us to do this already, it would be helpful to have this provided as a standard output "range" in the results.

To do this we suggest using the existing realistic scenario as a starting point, but with the following adjustments:

- Using R3.0 and R3.5 as two alternative variables
- Using a 90% vaccine take-up rate (but also as a nice to have also using a 85% take up rate)
- Keeping the realistic vaccine effectiveness assumptions, but also something slightly more optimistic on transmission (say 90%)?
- All other assumptions stay the same as now.

We would then be able to present a range of indicative outcomes associated with the different combinations of assumptions at different staging posts.

Different cuts of analysis

Policy question	**What conclusions can we draw from the work so far?**	**What is needed**
At what point of the vaccine roll-out would it be possible to start increasing covid case numbers (to a small degree) while being able to maintain a small number of negative health outcomes (i.e. 1-10 fatalities per year)? This question is relevant to phase 3 of the proposed border opening framework that the recent DPMC/Health led policy sprint has been considering.	The results indicate that there is likely a very limited window in which a small number of cases could be let in (without alert level restrictions) while maintaining only a small number of fatalities. Even once 90% of the whole population is vaccinated with 0.5 cases per day fatalities are not entirely eliminated. Table A5 of the *"A COVID-19 Vaccination Model for Aotearoa New Zealand – Appendix"* sets out that in the pessimistic scenario at R1.1, 0.5 cases per day would lead to hundreds of fatalities. However, the results do not show outcomes for a more realistic scenario at R1.1. However, these results exclude any control measures (including isolation and contact tracing).	It would be helpful to have modelling outputs to the following: A much lower daily incursion rate (there are border opening options that would allow us to only marginally increase risk). Suggest: - 5 incursion per month - 10 incursion per month Be able to see in one table the impacts associated with these incursions at more granular vaccine roll-out points: - Staging point 3 - Then successive points from that stage until whole population vaccinated.
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	might vary with these measures in place or not.	

Further analysis

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How would the distribution of outcomes look if the Maori population had a lower take-up of the vaccine overall.	Modelling not yet done.	Could we look at a scenario where Maori take up is: - 80% or 70% - While the rest of the population is at 90%
Homongenity	Sensitivity analysis has been done, which shows a large potential impact depending on assumptions. However, we do not have a good sense of what overall conclusion we should be drawing from this. While this isn't so relevant for overall high-level messages, at this point. It does become more important as we start to	TPM to consider and report back on how we should best think about the results across the two matrix, and if any further development of modelling approach on here is warranted/realistic.

	consider different opening choices/points.	

Agenda: COVID-19 Modelling Governance Group 14 May 2021

Chair: Bryan Chapple, Deputy Secretary, Macroeconomics and Growth, **The Treasury**

Members: **DPMC**: Cheryl Barnes, **MOH**: Ian Town, Talo Talosaga **MBIE:** Paul Stocks, **StatsNZ:** Vince Galvin **MSD:** Nic Blakeley, PMCSA: Juliet Gerrard.

1. **Welcome and apologies (Bryan)**

2. **Overview of vaccines/borders modelling results and next steps (George W/Chris N)**
Purpose: to review the key results of modelling so far, reaction from engagement with Ministers and next steps.

Context: The Steering Group have been continuing to engage with TPM as they further develop the work we reported on at the last meeting. We'll cover key results and what is being commissioned from here, for your feedback and direction.

Attached:
DPMC Slide Pack: Vaccines Modelling,
Vaccine Modelling Summary note

3. **Latest context on the international picture (Chris N)**

Purpose: to give the group context and visibility on the global COVID picture in the context of work on 'reconnecting New Zealand'

Context: Through The Treasury's contract with Wigram Capital, they have provided the Steering Group with an updated overview of the global picture looking at vaccine roll outs, effects on case numbers and fatalities, and unpicking the effect of lockdowns vs vaccination on those metrics. This is useful context to have in mind as we both consider vaccine efficacy in New Zealand and how borders re-open.

Key messages from the discussion with Wigram are outlined in this table below:

The good news	***But as usual a lot remains uncertain:***	***And there is a long way to go:***
• The US, UK and Israel are all at or around 50% vaccinated (at least a first dose) and are already seeing a significant reduction in cases and fatalities. This is despite increases in mobility that look to be at/close to pre-COVID levels. • The UK and Israel are reporting daily deaths in single figures or zero.	• The test for vaccines will come as mobility stays at elevated levels and unvaccinated young people return to school • Vaccine uptake is slowing in these countries, and making further progress will depend on getting to harder to reach/convince groups as well as younger people.	• India's case number curve looks to be bending but unless vaccination rates rise there will be another wave. • Countries using Sinovac aren't seeing positive results, with negative implications for global health outcomes as it is used more widely used in developing countries. E.g. Chile has vaccination rates close to the US but no equivalent drop in deaths.

Attached: Slide deck from Wigram Capital.

4. Strategic COVID19 Public Health Advice Group (George W)

Purpose: To discuss the operation of the Group so far and whether there is further support we can offer.

Context: The Group is working through its approach on, and demand for, modelling.

[TSY]

From: George Whitworth [DPMC]
Sent: Thursday, 16 September 2021 12:58 PM
To: Juliet Gerrard [DPMC]; Ian Town; Bryan Chapple [TSY]; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; Ruth Fairhall [DPMC]; 'vince.galvin@stats.govt.nz'; ^MBIE: Paul Stocks
Cc: ^EXT: Talosaga Talosaga; Gill.Hall@health.govt.nz; Pubudu Senanayake; Christopher Nees [TSY]; Harry Nicholls [TSY]; Patricia Priest; Alice Hume [DPMC]
Subject: FW: COVID strategy modelling catch up [Draft strategy and scenarios document]
Attachments: Modelling scenario strategies 1200 Thurs.docx

Hello Modelling Governance Group

I wanted to share with you the working draft for the scope of the next round of significant modelling work which primarily relates to our ongoing work with the TPM teams. This is the piece that will produce Doherty Institute or UoM/Blakeley -esque results for New Zealand, and as we discussed at the previous Governance Group discussion.

You'll note this is incomplete and has plenty of comments: this is a vehicle for documenting the conversations we have had in the Steering Group and for recording and iterating discussion with the TPM researchers. We have our next catchup with them tomorrow afternoon, as below.

Despite that, if you do have reactions at this time about the nature of the work (the strategies that we are outlining, the outcomes which they relate to, and the arrangement of "rules" which assemble to deliver these) then we'd be very happy to hear those and incorporate as the project progresses.

Some process points:

- We have arranged for regular weekly check-ins with Minister Verrall where Chris, Trish and I will update her on progress and deliverables over the next 1-2 months.
- I suggest that we also share the scoping document with Professor Skegg, but I will do that with a version from early next week which captures tomorrow's discussion with TPM and is much cleaner in terms of number of comments
- Trish will share with other colleagues in the Ministry who will be interested in being sighted on/inputting to this work at an early stage.

Thanks

George

George Whitworth
Principal Policy Advisor, COVID-19 Group
Department of the Prime Minister and Cabinet

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E george.whitworth@dpmc.govt.nz

DEPARTMENT OF THE PRIME MINISTER AND CABINET
TE TARI O TE PIRIMIA ME TE KOMITI MATUA

From: George Whitworth [DPMC]
Sent: Thursday, 16 September 2021 12:43 pm
To: Christopher Nees [TSY] <Chris.nees@treasury.govt.nz>; Patricia Priest <Patricia.Priest@health.govt.nz>; Pubudu Senanayake <Pubudu.Senanayake@stats.govt.nz>; ^EXT: Talosaga Talosaga <Talosaga.Talosaga@health.govt.nz>; Harry Nicholls [TSY] <Harry.Nicholls@treasury.govt.nz>; shaun.hendy@auckland.ac.nz; Dion O'Neale <d.oneale@auckland.ac.nz>; Emily Harvey <emily@me.co.nz>; Patricia Priest <patricia.priest@otago.ac.nz>; Michael Plank <michael.plank@canterbury.ac.nz>
Cc: Tim Ng [TSY] <tim.ng@treasury.govt.nz>; Hemant Passi [TSY] <Hemant.Passi@treasury.govt.nz>; pmcsa <pmcsa@auckland.ac.nz>; Pippa Scott <Pippa.Scott@health.govt.nz>; Oliver Maclaren <oliver.maclaren@auckland.ac.nz>; Nicholas Steyn <nicholas.steyn@auckland.ac.nz>
Subject: RE: COVID strategy modelling catch up [Draft strategy and scenarios document]

[UNCLASSIFIED]

Hi all

With thanks to my colleagues on the steering group for iterating thinking over multiple versions, I've attached a document which aims to crystallise the commissioning around this next chunk of COVID-19 strategy modelling. This should be consistent with our conversations to date, with the rough and ready work that the BPM team had been producing, and hopefully progresses thinking on some of the goalposts in whatever sport it is we are playing.

This document also about documenting our thinking and sharing it with less engaged colleagues. On that basis, there are a bunch of unresolved comments, and the content of pages 1,2,3 will be pretty familiar to this group. You will likely want to commit a little more attention to 4,5,6.

In terms of what it would be good to achieve at tomorrow's catchup:

- Discussion on the question of "rules-based outcomes" vs "outcomes-based rules", whether both are useful in different ways, and whether it makes sense to do one ahead of the other.
- Agreement on a small number of initial scenarios (strategies x assumptions) with defined rules for some initial modelling results in the near-term.
- Discussion of what we can expect from the BPM and NCM teams in relation to this work, and in particular whether there are outputs of the NCM that can help inform the BPM, and when we can expect it.

Very happy to discuss, as ever.

George

George Whitworth
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DEPARTMENT OF THE PRIME MINISTER AND CABINET
TE TARI O TE PIRIMIA ME TE KOMITI MATUA

[TSY]

From: Harry Nicholls [TSY]
Sent: Thursday, 28 October 2021 7:10 PM
To: Christopher Nees [TSY]; Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; vince.galvin@stats.govt.nz; Ian Town; pmcsa; ^EXT: Talosaga Talosaga; J.gerrard@auckland.ac.nz
Cc: George Whitworth [DPMC]; Gill Hall; Pubudu Senanayake; Patricia Priest; ea@pmcsa.ac.nz
Subject: RE: Agenda and papers for Friday's Covid-19 Modelling Governance Group
Attachments: 4558125_Summary of recent modelling insights and updates_v2.docx

Kia ora koutou – apologies for the late circulation. Attached is the paper for item 4 tomorrow.

TE TAI ŌHANGA
THE TREASURY

Harry Nicholls | Kaitātari Matua – Senior Analyst | Te Tai Ōhanga – The Treasury
Economic Policy, Economic Strategy Directorate
Tel: +s9(2)(k) | Email/IM: Harry.Nicholls@treasury.govt.nz

From: Christopher Nees [TSY] <Chris.nees@treasury.govt.nz>
Sent: Wednesday, 27 October 2021 4:54 PM
To: Bryan Chapple [TSY] <Bryan.Chapple@treasury.govt.nz>; ^MBIE: Paul Stocks <Paul.Stocks@mbie.govt.nz>; ^MSD: Nic Blakeley <nic.blakeley005@msd.govt.nz>; Cheryl Barnes [DPMC] <Cheryl.Barnes@dpmc.govt.nz>; vince.galvin@stats.govt.nz; Ian Town <Ian.Town@health.govt.nz>; pmcsa <pmcsa@auckland.ac.nz>; ^EXT: Talosaga Talosaga <Talosaga.Talosaga@health.govt.nz>; J.gerrard@auckland.ac.nz
Cc: George Whitworth [DPMC] <George.Whitworth@dpmc.govt.nz>; Gill Hall <Gill.Hall@health.govt.nz>; Pubudu Senanayake <Pubudu.Senanayake@stats.govt.nz>; Patricia Priest <patricia.priest@health.govt.nz>; ea@pmcsa.ac.nz; Harry Nicholls [TSY] <Harry.Nicholls@treasury.govt.nz>
Subject: Agenda and papers for Friday's Covid-19 Modelling Governance Group

Kia ora koutou

Please find attached an agenda and papers for Friday, with the paper for item 4 to follow tomorrow.

Ngā mihi

Chris Nees| Principal Advisor | Economic Strategy Directorate |Te Tai Ōhanga – The Treasury
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Visit us online at https://treasury.govt.nz/ and follow us on Twitter, LinkedIn and Instagram

I do not work on Thursdays.

TE TAI ŌHANGA
THE TREASURY

[TSY]

From: Christopher Nees [TSY]
Sent: Wednesday, 27 October 2021 4:54 PM
To: Bryan Chapple [TSY]; ^MBIE: Paul Stocks; ^MSD: Nic Blakeley; Cheryl Barnes [DPMC]; vince.galvin@stats.govt.nz; Ian Town; pmcsa; ^EXT: Talosaga Talosaga; J.gerrard@auckland.ac.nz
Cc: George Whitworth [DPMC]; Gill Hall; Pubudu Senanayake; Patricia Priest; ea@pmcsa.ac.nz; Harry Nicholls [TSY]
Subject: Agenda and papers for Friday's Covid-19 Modelling Governance Group
Attachments: 4558115_Agenda - COVID Modelling Governance Group meeting 29 October.DOCX; Possible Scenario of Outbreak Trajectory and Potential 221021 1500.pdf; Slides for 2710 modelling update.pptx

Kia ora koutou

Please find attached an agenda and papers for Friday, with the paper for item 4 to follow tomorrow.

Ngā mihi

Chris Nees| Principal Advisor | Economic Strategy Directorate |Te Tai Ōhanga – The Treasury
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I do not work on Thursdays.

TE TAI ŌHANGA
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