Know-C19

A policy, health and implementation response to COVID-19

Modelling the Victorian roadmap

Since July 2021 Melbourne has experienced a resurgence in delta variant COVID-19 cases. Despite a lockdown being introduced on 5 August, cases continue to grow, and at 17 September daily diagnoses have reached a 7-day average of 454.

With Victoria's COVID-19 strategy shifting away from COVID-zero, protecting the health of the population will require achieving high vaccination coverage as quickly as possible, maintaining control of the epidemic to protect the vulnerable, and ensuring that the health system has capacity to provide care to all who need it. ***An important question is: as vaccine coverage increases, how best can restrictions be eased that prevents health system capacity from being exceeded?***

The *Covasim* model was used to simulate options for easing of restrictions over the October-December period. Model inputs included data on demographics, contact networks, workforce composition, contact tracing systems and age-specific vaccination rates. As well as options for easing restrictions, additional policies around vaccine allocation and testing were examined to determine potential approaches to further reduce the epidemic peak.

Scenarios were run to estimate the number of COVID-19 infections, hospitalisations and ICU requirements in Melbourne:

- **Maintained lockdown:** A counterfactual scenario to set baseline estimates from which restrictions are eased.
- **Roadmap**: School and childcare returns throughout October; increased outdoor activities at 70% two-dose vaccine coverage (people 16+ years); retail and indoor activities with density limits commence at 80% adult vaccine coverage; and mandatory vaccination of authorized workers, teachers, childcare workers, parents of children in childcare, hospitality workers, hospitality patrons.
- **Roadmap with additional testing:** The roadmap scenario but assuming vaccinated people continue to seek symptomatic testing at the same rate as non-vaccinated people, even for mild symptoms.
- **Roadmap with a 15% reduction in non-household transmission.** The roadmap scenario, but with an assumption that a 15% reduction in non-household transmission could be achieved immediately and sustained.

<u>*Key findings*</u>

1. **Even without any easing of restrictions, there is a moderate risk of exceeding health system capacity**
   - Based on the current epidemic growth rate, a peak in 7-day average daily diagnoses of 1400-2900 is estimated to occur between 19-31 October
   - Corresponding peaks in hospital and ICU demand were 1200-2500 and 260-550 respectively, with 24% of simulations resulting in hospital demand exceeding 2500 beds.
2. **In the roadmap scenario, the significant easing of restrictions at 80% vaccine coverage led to 63% of simulations exceeding 2500 hospital demand, and resulted in a second epidemic peak over mid-December**
3. **High rates of symptomatic testing among people who are vaccinated could reduce the impact on the health system**
   In a scenario with vaccinated people testing at the same rate as unvaccinated people, the risk of >2500 hospital demand was reduced from 63% to 29%. However, this may be difficult to achieve in practice.
4. **If a 15% reduction in non-household risk could be achieved and sustained through a variety of additional targeted public health and testing interventions, the risk of >2500 hospital demand could be reduced to 18%**
5. **When 80% adult vaccine coverage is reached, the case numbers, hospital and ICU numbers can provide a guide as to the likelihood of the health system capacity being exceeded** and whether restrictions can be safely eased consistent with the roadmap or whether a more staggered approach may be required.
6. **Due to uncertainty about whether the epidemic growth rate will be sustained, seasonal impacts and vaccine efficacy parameters against the delta strain, updated projections are required as more data becomes available**
   Decisions to ease restrictions should be based on the latest epidemiological and health system information.

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Background and aims

Since July 2021 Melbourne has experienced a resurgence in delta variant COVID-19 cases. Despite a lockdown being introduced on 5 August, cases continue to grow, and at 17 September daily diagnoses have reached a 7-day average of 454.

With Victoria's COVID-19 strategy shifting away from COVID-zero, protecting the health of the population will require achieving high vaccination coverage as quickly as possible, maintaining control of the epidemic to protect the vulnerable, and ensuring that the health system has capacity to provide care to all who need it. ***An important question is: as vaccine coverage increases, how best can restrictions be eased that prevents health system capacity from being exceeded?***

The *Covasim* model was used to simulate options for easing of restrictions over the October-December period. Model inputs included data on demographics, contact networks, workforce composition, contact tracing systems and age-specific vaccination rates. Model parameters for transmission, testing and the impact of packages of restrictions were calibrated to fit observed epidemiological data over the current and past outbreaks. As well as options for easing restrictions, additional policies were examined to determine potential approaches to further reduce the epidemic peak.

Scenarios were run to assess different options for easing restrictions, and their impact on health outcomes as well as the expected peak hospital and ICU demand.

Method

<u>Model overview</u>

We used an established agent-based microsimulation model, *Covasim* [1], developed by the Institute for Disease Modelling (USA) and previously adapted by the Burnet Institute to model epidemics in Melbourne [2-4]. The model is available online [5]. In brief, agents in the model are assigned an age (which affects their susceptibility to infection and also their likelihood of being symptomatic), a household, a school (for people age 5-17) or a workplace (for people over 18, up to 65), and they participate in a number of community activities that may include attending restaurants, pubs, places of worship, community sport, and small social gatherings. Details of included contact types, network structures, transmission probabilities, and contact tracing capability (which vary by setting) are provided in the appendix at the end of this report.

<u>Calibration</u>

Model parameters for transmission and testing were calibrated to data on daily new detected cases, hospitalisations and ICU from the delta COVID-19 epidemic wave in Melbourne over the July-September 2021 period [6]. The impact of different policy changes associated with the roadmap were estimated from calibration to the epidemic wave in 2020 [2-4].

<u>Interventions</u>

The model includes testing, contact tracing and quarantine of close contacts and their household contacts, isolation of confirmed cases, masks, physical distancing policies in venues (e.g., the 4 square metre rule), policy restrictions to prevent or reduce transmission in different settings (e.g., closing schools or workplaces) and vaccination programs. The implementation of each of these interventions is described in the following sections.

<u>Symptomatic testing probability (COVID-19 cases)</u>

All people with severe disease are assumed to be tested. For people with mild symptoms, the model includes a per-day probability of seeking a test, which is determined through model calibration. Based on the current outbreak, test-seeking probability was estimated to be 0.034 per day of mild symptoms. This suggests that among people who have mild symptoms *and are not identified through contact tracing or exposure site notification*, 24% will seek testing during their symptomatic period.

Contact tracing

The model uses daily time steps and the testing/contact tracing system was approximated as follows:

1. Day 0: Test is taken by index case
2. Day 1 (24 hours following test): Positive test results are returned, index case is notified and enters isolation.
3. Day 2 (48 hours following test being taken^): Contact tracing completed, with contacts having a setting-specific probability of being detected (Table S1), reflecting differences in the level of difficult in identifying contacts in that network (e.g. households vs public transport contacts). Identified contacts are tested and quarantined for 14 days regardless of test results, along with their entire households. Contacts are additionally tested on day 11 of quarantine, regardless of symptoms.
4. Day 3 (72 hours following test): Test results for contacts become available, and any contacts who returned a positive initial test would then have their contacts traced within the next 24 hours, in the same manner as the index case.

It was assumed that contact tracing deteriorated as case numbers increased. Caps on contact tracing assumed: at 0, 25, 75, 150 and 500+ cases per day, 100%, 80%, 50%, 30% or 20% of detected cases are subject to the above algorithm. The cap does not apply to household, school or childcare contacts who are assumed able to conduct their own tracing.

Virus strain

The model was calibrated to the transmission of the delta variant currently circulating in Victoria. The incubation period was shortened to a mean time from exposure to becoming infectious of 3.71 days, compared to 4.50 days for the wild type virus [8]. Disease prognoses (e.g., age-specific probability of requiring hospitalization, ICU or of dying) were updated to reflect the increased severity of the strain [9] (adjusted odds ratio for hospitalization, ICU and death of 2.08 relative to wild type; see appendix).

Vaccine properties

In the model, vaccination acts to reduce the probability of acquiring an infection when a contact occurs with an infectious case, as well as the probability of developing symptoms (both mild and severe) for people who are vaccinated and become infected. There remains significant uncertainty in these parameters as evidence continues to emerge. The assumed efficacy values used in this modelling are below; they are based on estimates for vaccines against the delta variant from Imperial College London, London School of Hygiene and Tropical Medicine and Warwick University [7].

Table 1: Vaccine efficacy parameters against the delta variant

Vaccine impact	Infection	Onward transmission	Symptoms	Hospitalization	ICU	Death
Overall protection: Pfizer 1	47%	33%	47%	71%	71%	71%
Overall protection: Pfizer 2	80%	56%	85%	87%	89%	92%
Overall protection: AstraZeneca 1	43%	24%	43%	69%	69%	69%
Overall protection: AstraZeneca 2	62%	45%	71%	86%	88%	90%

The vaccine's prevention of infection is approximated as "leaky", meaning that each person vaccinated has reduced but non-zero risk of becoming infected based on the vaccine efficacy (as opposed to an "all or nothing" vaccine, where 80% efficacy means that 80% of people have perfect protection and 20% have no protection).

Multiple vaccine interventions were implemented in the model, with each vaccine intervention defined by vaccine type and time between doses (e.g. AstraZeneca 12-weeks). People who received their first vaccination were assumed to receive their second at the scheduled time, and vaccine immunity (protection against infection and disease) was modelled to increase over time. The time to reach the estimated peak efficacies reported in Table 1 was dependent on vaccine type and time between doses, and the immunity profile assumed for the Pfizer 3, 6 and 8-week and the AstraZeneca 12 and 6-week vaccinations are shown in Figure 1.

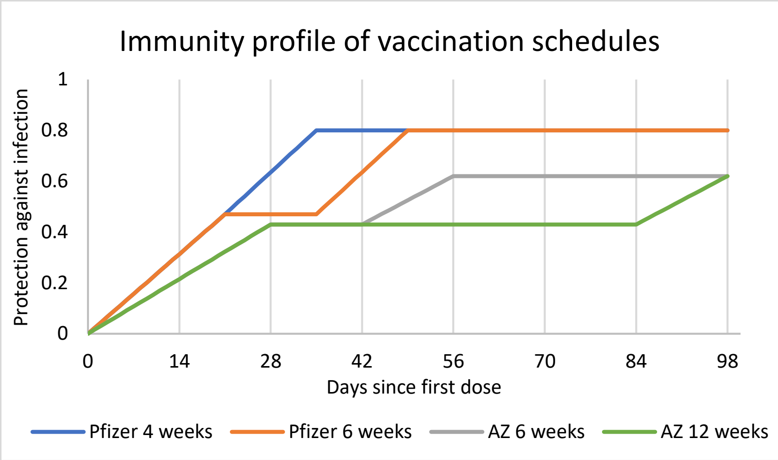

Figure 1: Vaccination immunity profile over time. Vaccinations were modelled according to vaccine type and time between doses and had a time-varying protection that depended on the vaccine type and time between doses.

An independent behavioural factor was also modelled where people who are vaccinated had a 50% reduction in their probability of seeking testing if they had mild symptoms, compared to people who were not vaccinated. Vaccinated individuals were assumed to still test and quarantine the same as non-vaccinated people if they were identified as a close contact of a confirmed case.

Vaccination rollout

Vaccine allocation in the model was age-specific and based on historic Pfizer and AstraZeneca doses delivered from Australian Immunization Registry (AIR) data, as well as assumptions about the rollout rate going forward (Figure 2). Key milestone assumptions among adults 16+ years in the model include

- 70% two-dose coverage being reached on 31 Oct
- 80% two-dose coverage being reached on 7 Nov

The vaccine rollout was modelled to continue beyond 80%, to reach 92% coverage among adults 16+ years by the end of 2021 (95% coverage among people over 60 years; 85% coverage among people aged 16-59). It was assumed that everyone who received a first dose would receive a second dose (albeit with different schedules).

To approximate the concentration of infections from August to mid-Sep in geographical areas with lower vaccine coverage, the model was calibrated and initialized with population-weighted coverage values representing those areas, and then modelled to catch up to the Melbourne average by 80% first dose. This means that the model population approximates the areas where the infections are occurring at the moment but assumes a spread throughout Melbourne over time.

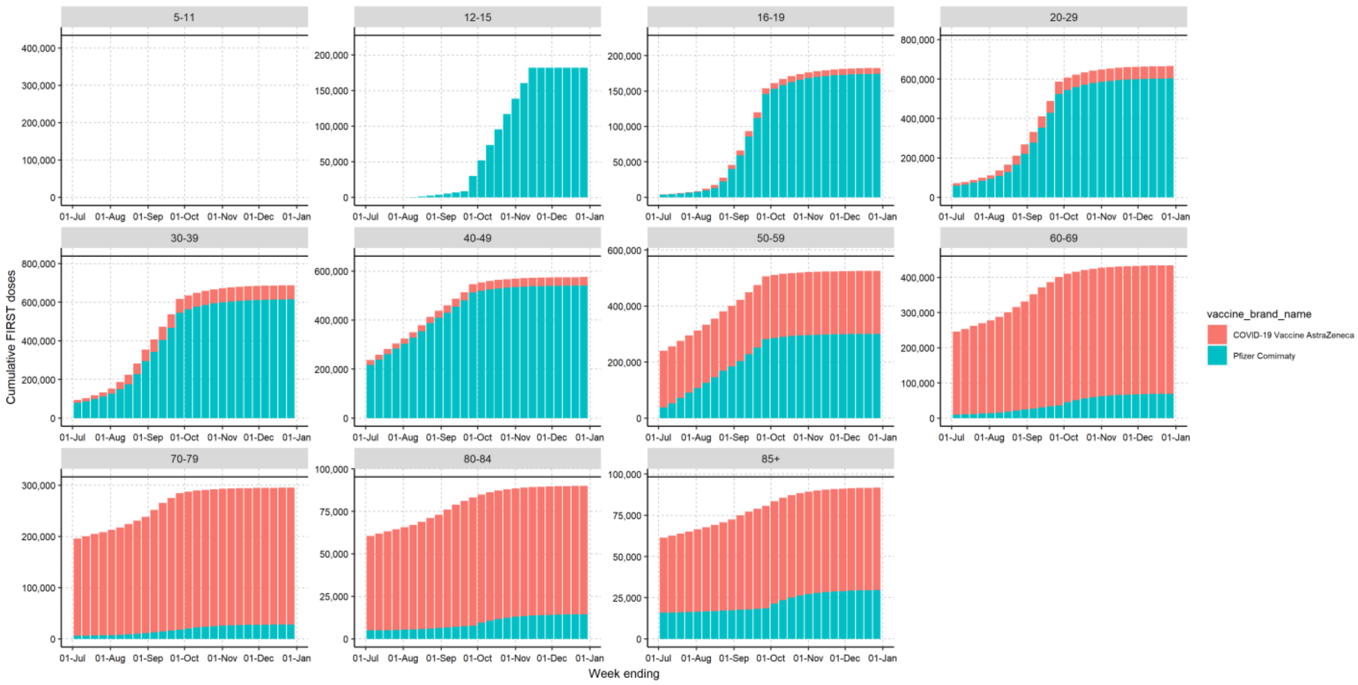

Figure 2: Cumulative FIRST dose coverage, used for model inputs. Second dose coverage is based on actual and proposed future changes to dose scheduling, and makes an approximation that everyone receiving a first dose receives a second dose. Red: AstraZeneca. Green: Pfizer.

Mandatory vaccination

Mandatory vaccination were implemented by excluding unvaccinated people from participating in activities subject to a vaccine mandate (e.g. teachers, or people attending hospitality) rather than assuming any additional vaccines. It was assumed to have 95% compliance.

Scenarios

Projections were run for Melbourne for the following scenarios:

- **Maintain lockdown.** A counterfactual scenario to set baseline estimates from which restriction are eased.
- **Roadmap.** Schools returning throughout October (Table 3); outdoor activities commencing at 70% adult 2-dose vaccine coverage; and density limits at 80% adult 2-dose vaccine coverage (Table 2). Roadmap scenario includes mandatory vaccines for authorized workers, teachers, childcare workers, parents of childcare workers, hospitality workers and hospitality patrons (95% compliance).
- **Roadmap with increased testing among vaccinated**. Roadmap scenario, but vaccinated people continue to seek symptomatic testing at the same rate as non-vaccinated people, even for mild symptoms.
- **Roadmap with reduction in non-household transmission**. Roadmap scenario, but with an assumption that a 15% reduction in non-household transmission could be achieved immediately and sustained. This would require a package of targeted public health interventions.

For each scenario, 1000 simulations were run, sampling from the likely range of transmission parameters.

Restriction policies

For the main roadmap analysis, the model was based around the restriction levels in Table 2.

Table 2: Roadmap restrictions being modelled.

	Lockdown	School roadmap (starting 5 Oct)	Outdoor activities 70% two-dose vaccine coverage 16+ years	Density limits 80% two-dose vaccine coverage 16+ years
Childcare	Authorized only	Open for people with both parents vaccinated 25 Oct	Open	Open
Schools	Online	See school roadmap	See school roadmap	In person
Café/restaurant	Take-away	Take-away	Outdoor only with 4sqm	4sqm
Pub/bar	Take-away	Take-away	Outdoor only with 4sqm	4sqm
Retail	Essential only	Essential only	Essential only	4sqm
Places of worship	Closed	Closed	Outdoor only with 4sqm	4sqm
Community sport	Closed	Closed	Open	Open
Outdoor gatherings	2 for exercise	2 for exercise	<50	<100
Construction	Restricted	Restricted	Open	Open
Non-retail work	Authorized only	Authorized only	Authorized only	Work from home if possible
Entertainment	Closed	Closed	Outdoor only, 10 per group	4sqm
Social	None	None	None	5 visitors to the home
Mobility	5km	10km	No restrictions	No restrictions
Masks	Mandatory	Mandatory	Mandatory	Indoors only

Table 3: Incremental opening of schools and childcare captured in the model.

Year level		5 Oct	18 Oct	26 Oct	5 Nov	18-Dec
Childcare	Authorized only	Authorized only	Authorized only	Open for people with both parents vaccinated	Open	Open
Prep	Online learning	Online learning	Three days per week	Three days per week	In person	Closed
1-2	Online learning	Online learning	Two days per week	Two days per week	In person	Closed
3-4	Online learning	Online learning	Online learning	Two days per week	In person	Closed
5-6	Online learning	Online learning	Online learning	Two days per week	In person	Closed
7	Online learning	Online learning	Online learning	Five days per week	In person	Closed
8-9	Online learning	Online learning	Online learning	Two days per week	In person	Closed
10	Online learning	Online learning	Online learning	Two days per week	In person	Closed
11	Online learning	Online learning	Online learning	Five days per week	In person	Closed
12	Online learning	Five days per week	Five days per week	SWOT VAC		

Results

There is considerable uncertainty in future projections as the outbreak is still in an early growth stage; however, if the current R_{eff}, vaccine rollout and restrictions were maintained, a peak in 7-day average daily diagnoses could be expected around late-October (Figure 3). In 24% of simulations, hospital demand exceeded 2500 (Table 4), suggesting that easing of restrictions must be done carefully to avoid overwhelming the health system.

The roadmap scenario (schools returning throughout October; outdoor activities commencing at 70% adult two-dose vaccine coverage; density limits at 80% adult two-dose vaccine coverage; and mandatory vaccines) created significant additional risk, resulting in a second epidemic peak in mid-December (Figure 4). The second peak was largely attributable to the easing of restrictions at 80% two-dose adult vaccine coverage, which had a shift in R_{eff} due to the increased indoor mixing and multiple policies being eased at once (compared with the final scenario in Table 4 where this easing step does not happen).

Increased testing among vaccinated people was able to mitigate the potential for a resurgence (Figure 5) and reduce the risk of exceeding health system capacity (Table 4). In practice this may not be realistic; however the more that testing can be maintained the more risk that can be mitigated.

Similarly, the roadmap with a 15% reduction in non-household transmission (Figure 6) also had lower risk. The specifics of how a 15% reduction in non-household transmission could be achieved and sustained is unclear but would likely require multiple targeted approaches with small impacts in combination; for example this might include increased testing, better quality masks, targeting of vaccines to higher COVID-19 risk occupations, increased outdoor classes in schools, and other gains. Nevertheless, this scenario demonstrates the value of even small reductions in transmission towards managing the risks associated with easing restrictions.

Table 4: Outcomes of the modelled roadmap, with different interventions in place. For each quantity, the inter-quartile range observed in the simulations is also reported.

	Cases		Hospital		ICU		Deaths
Easing plan	Peak 7-day average	Peak date for 7-day average	Peak demand	Percentage of simulations exceeding 2500 beds	Peak demand	Percentage of simulations exceeding 625 beds	Jul-Dec 2021
Maintain lockdown	1960 (1359-2938)	25 Oct (19 Oct, 31 Oct)	1666 (1184-2474)	24%	360 (257-551)	19%	964 (669-1426)
Roadmap Schools open throughout October Outdoors at 70% 4 sqm rule at 80% Vaccine mandates	4543 (2778-6761)	15 Dec (07 Dec, 22 Dec)	3150 (1950-4400)	63%	706 (462-953)	58%	2202 (1455-3152)
Roadmap with increased testing *Roadmap plus*: Vaccinated people maintain testing with mild symptoms	2474 (1461-4388)	10 Dec (18 Oct, 21 Dec)	1700 (1097-2750)	29%	405 (253-644)	27%	1323 (828-2044)
Roadmap with 15% reduction in non-household transmission *Roadmap plus*: Assumption that a 15% reduction can be achieved and maintained	1708 (1115-3095)	26 Nov (15 Oct, 16 Dec)	1372 (944-2200)	18%	325 (211-516)	17%	1061 (681-1724)
Roadmap without the 80% step *Roadmap except*: No additional easy occurs when 80% adult coverage is reached	1941 (1361-2906)	25 Oct (19 Oct, 31 Oct)	1648 (1182-2428)	24%	366 (256-535)	17%	936 (662-1375)

NB: Median in figures may appear slightly different to table, because the different calendar date of simulation peaks means that the median of [peak values across simulations] is not the same as the peak of [the line generated by plotting the median value at each point]. Figures are for visualization only (see appendix).

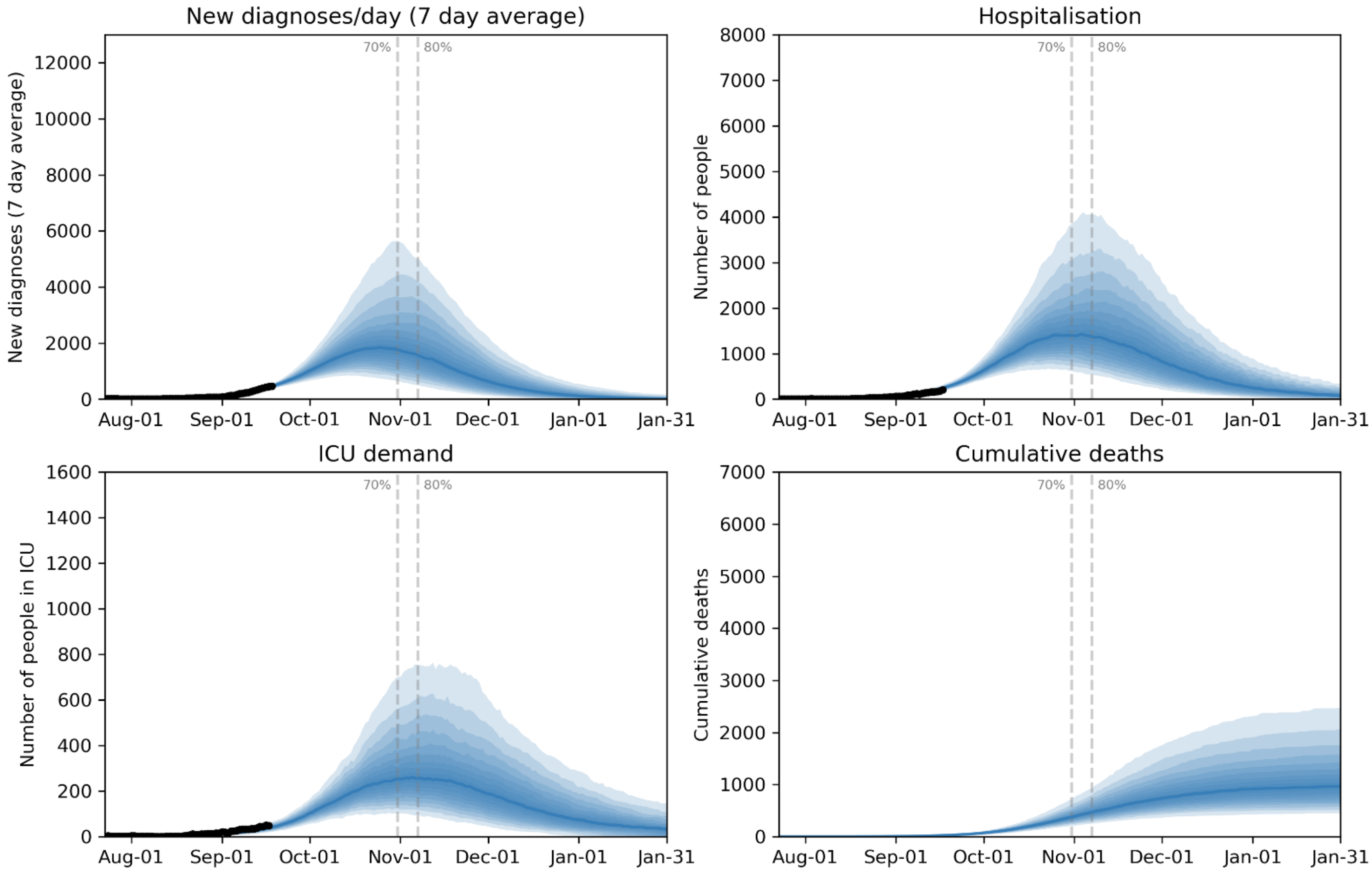

Figure 3: Maintain lockdown scenario. Figures show a counterfactual scenario where the lockdown is maintained, to provide a baseline estimate for easing of restrictions. Projected 7-day average daily diagnoses (top), hospital utilization (top-right), ICU utilization (bottom-left), and cumulative deaths (bottom-right). Dashed vertical lines represent estimated dates of reaching 70% and 80% two-dose coverage among people 16+ years.

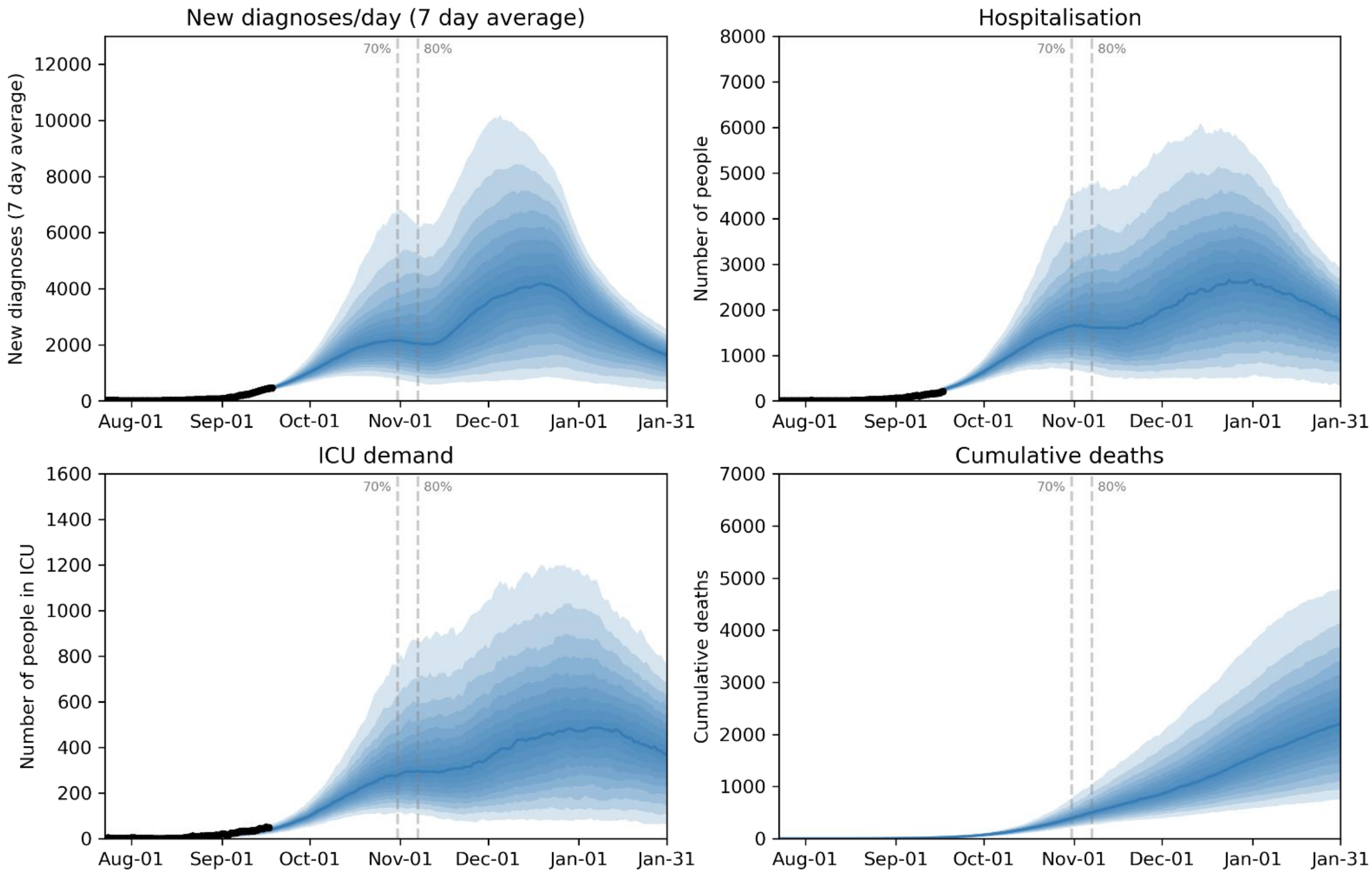

Figure 4: Roadmap scenario. Includes schools returning to in person learning throughout October; childcare returning and mobility restrictions easing in October; limited outdoor gatherings at 70% two-dose vaccine coverage among people 16+ years; indoor gathering with density limits at 80% two-dose coverage among people 16+ years (Table 2 and Table 3); and mandatory vaccine requirements. Dashed vertical lines represent estimated dates of reaching 70% and 80% two-dose coverage among people 16+ years.

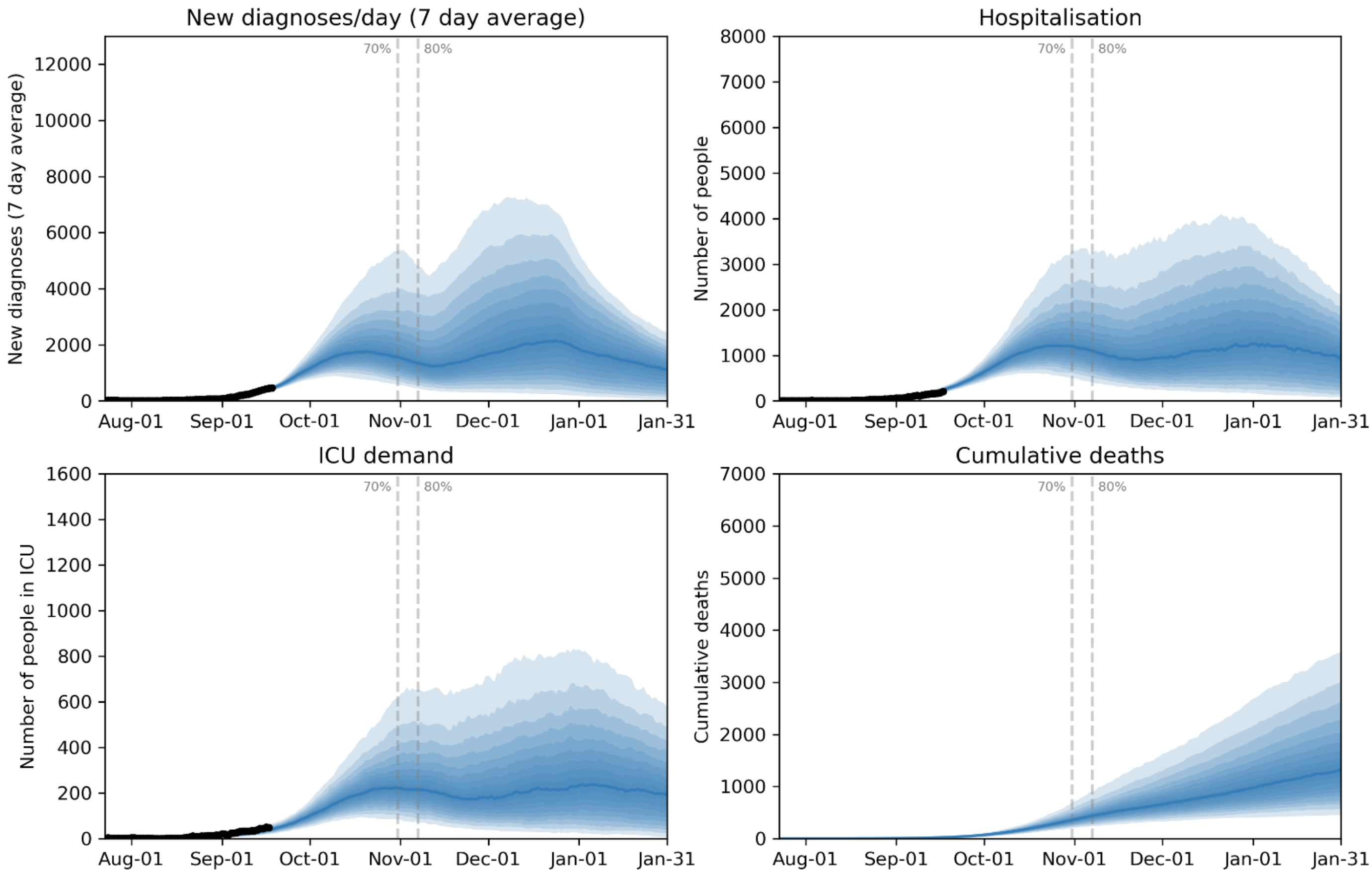

Figure 5: Roadmap scenario with increased testing. Eased restrictions based on Table 2 and Table 3 and mandatory vaccines; and *in addition, vaccinated people are assumed to be equally as likely to seek symptomatic testing as much as unvaccinated people, even for mild symptoms*. Dashed vertical lines represent estimated dates of reaching 70% and 80% two-dose coverage among people 16+ years.

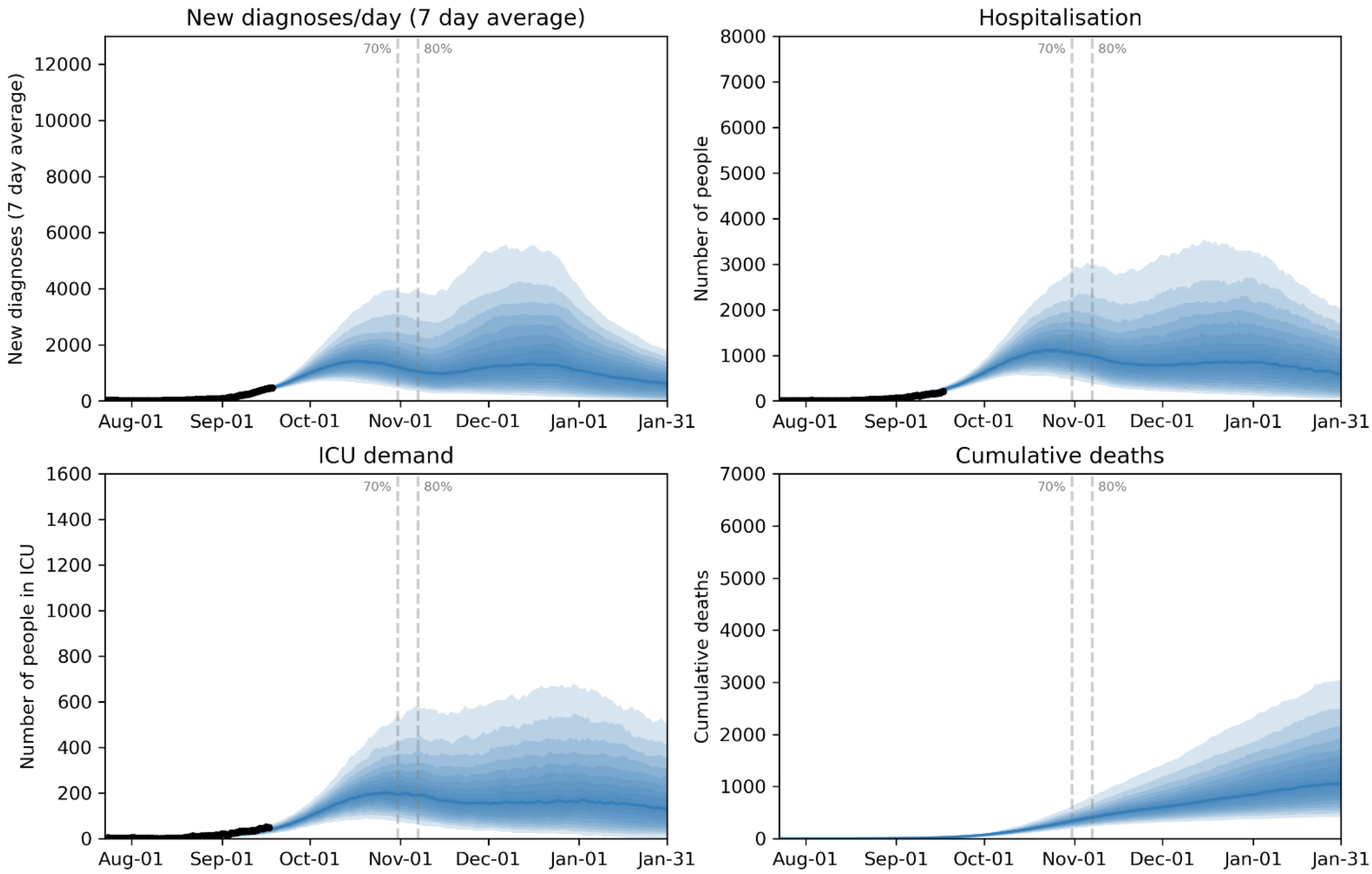

Figure 6: Roadmap scenario with a 15% reduction in non-household transmission. Eased restrictions based on Table 2 and Table 3 and mandatory vaccines; and *in addition, an assumed 15% reduction in non-household transmission is implemented and sustained*. It is unclear how this could be achieved, but would likely be a combination of targeted public health measures. This scenario illustrates that actions taken now can provide benefits later. Dashed vertical lines represent estimated dates of reaching 70% and 80% two-dose coverage among people 16+ years.

Decision making at 80% two-dose coverage among people 16+ years

Running 1000 simulations for each scenario produces a wide distribution of results, reflecting uncertainty in how the epidemic will unfold. Table 4 reports the median and inter-quartile range of outcomes across these simulations, representing what are the more likely outcomes based on data available as at 17 September. Some of the individual simulations lead to very bad outcomes, while others are much more manageable. Additional information in the coming weeks will make it clearer which individual trajectory we are on, which has implications for the risks associated with further easing restrictions.

To inform decision-making, we extracted conditional outcomes (Figure 7) to estimate how peak hospital and ICU demand varies depending on the state of the epidemic when 80% two-dose vaccine coverage is reached among people 16+ years. For example:

- In simulations where 1000-1500 hospital beds were in use at the time 80% vaccine coverage was reached, easing restrictions resulted in a peak hospital demand of >2500 in approximately 45% of simulations in the roadmap scenario (Figure 7; left, red).
- If 1500-2000 hospital beds were in use at the time 80% vaccine coverage was reached, easing restrictions resulted in a peak hospital demand of >2500 in approximately 80% of simulations in the roadmap scenario (Figure 7; left, red).

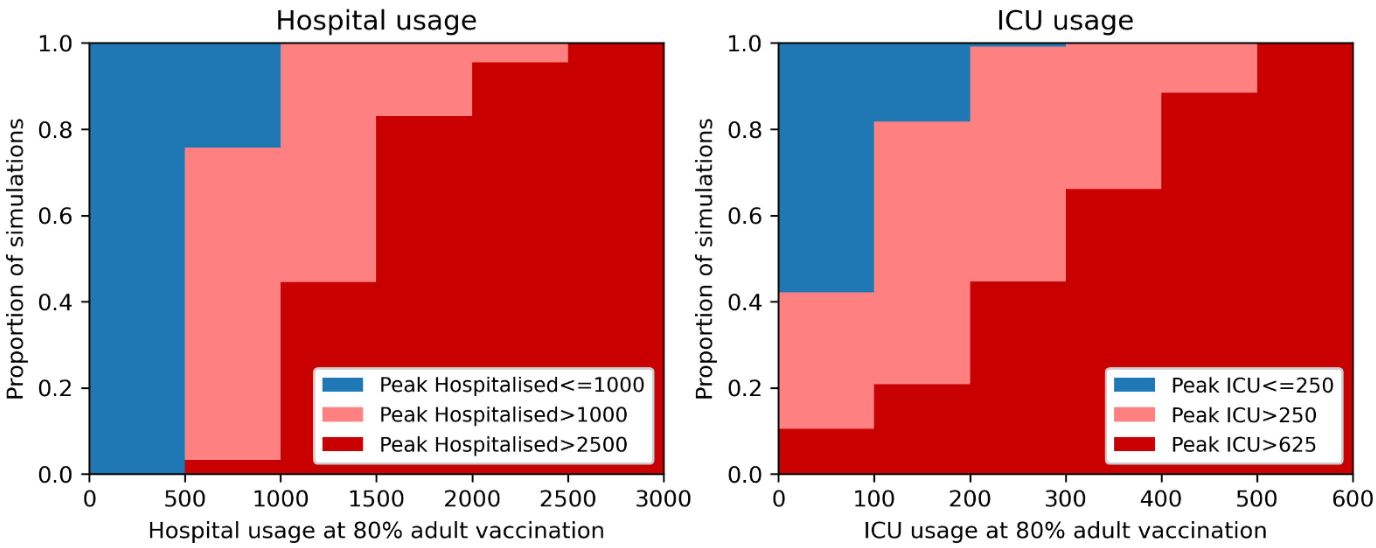

Figure 7: 80% two-dose vaccine coverage among people 16+ years time point. Estimated peak hospital and ICU demand, based on hospital and ICU demand at 80% two dose coverage. Left: proportion of simulations resulting in peak hospital demand <1000 (blue), 1000-2500 (salmon) or >2500 (red) for an observed hospital demand at the 80% coverage time point. Right: proportion of simulations resulting in peak ICU demand <250 (blue), 250-625 (salmon) or >625 (red) for an observed ICU demand at 80% coverage.

Are the outcomes likely to be optimistic or pessimistic?

Models make simplifying assumptions to approximate the real world, particularly where data are not available. Some of these assumptions may lead to the model projections being optimistic or pessimistic compared to what may actually occur. For example, compliance with vaccine mandates in Australian settings is as yet unknown; in the roadmap scenario 95% compliance has been assumed, but the roadmap may be slightly optimistic depending on how successfully it can be implemented. To best interpret the model outputs, it is useful to understand some of the main assumptions that may make these projections optimistic or pessimistic.

Optimistic assumptions

The results could be optimistic (meaning the real world will be worse than estimated) because we have assumed:

- Schools and childcare can achieve a 50% reduction in transmission risk through ventilation and other mechanisms
- No waning of vaccine immunity over time
- No quarantine or testing exemptions have been included for vaccinated people (i.e. vaccinated people continue to be required to quarantine for 14 days if they are identified as contacts)
- Compliance does not further reduce over time (33% of people are assumed to have had between household contacts in the current lockdown / model calibration period)
- 95% compliance with vaccine mandates
- Schools and childcare are able to conduct their own contact tracing
- Vaccines are delivered equally across all sub-population groups. It is possible that people who are more concerned about COVID-19 and are minimizing their number of contacts to lower their COVID-19 risk may be getting vaccinated before people who and less concerned about COVID-19 and are at higher risk.

Pessimistic assumptions

Conversely, the results could be pessimistic (meaning the real world will be better than estimated) because we have assumed:

- No impact of seasonality, when it is possible that warmer weather may reduce transmission (but unquantified at the moment).
- The current epidemic growth rate will continue (with the exception of declines due to vaccine immunity), when it is possibly biased by recent infections being concentrated in communities with below average vaccine coverage.

Uncertain assumptions

In addition, the results could be either optimistic *OR* pessimistic because:

- Average duration of stay in hospital and ICU is unknown. If it were longer or shorter than we have estimated (e.g. average 11 days in ICU, see appendix) then this would increase or decrease peak demand.
- Vaccine efficacy assumptions may be better or worse than the parameters we are using (Table 1), but are based on best estimates at the time of analysis.

Conclusions

1. **Even without any easing of restrictions, there is a moderate risk of exceeding health system capacity**
    - Based on the current epidemic growth rate, a peak in 7-day average daily diagnoses of 1400-2900 is estimated to occur between 19-31 October
    - Corresponding peaks in hospital and ICU demand were 1200-2500 and 260-550 respectively, with 24% of simulations resulting in hospital demand exceeding 2500 beds.
2. **In the roadmap scenario, the significant easing of restrictions at 80% vaccine coverage led to 63% of simulations exceeding 2500 hospital demand, and resulted in a second epidemic peak over mid-December**
3. **High rates of symptomatic testing among people who are vaccinated could reduce the impact on the health system**

    In a scenario with vaccinated people testing at the same rate as unvaccinated people, the risk of >2500 hospital demand was reduced from 63% to 29%. However, this may be difficult to achieve in practice.
4. **If a 15% reduction in non-household risk could be achieved and sustained through a variety of additional targeted public health and testing interventions, the risk of >2500 hospital demand could be reduced to 18%**
5. **When 80% adult vaccine coverage is reached, the case numbers, hospital and ICU numbers can provide a guide as to the likelihood of the health system capacity being exceeded** and whether restrictions can be safely eased consistent with the roadmap or whether a more staggered approach may be required.
6. **Due to uncertainty about whether the epidemic growth rate will be sustained, seasonal impacts and vaccine efficacy parameters against the delta strain, updated projections are required as more data becomes available**

Decisions to ease restrictions should be based on the latest epidemiological and health system information.

Limitations

The findings presented are derived from an individual-based model, which is an imperfect representation of the real world.

- Results are based on model inputs up to 17 September 2021. As the outbreak evolves and more data becomes available, the uncertainty reduces and it becomes clearer which trajectory we are on.
- There is uncertainty in the average length of stay in hospital and ICU, and this would impact estimates of peak hospital and ICU demand.
- Results do not include seasonal effects, which are unknown.
- Results do not include reduced compliance with restrictions over time. In particular, towards the end of our projections, we have assumed that testing, contact tracing and quarantine continues despite high vaccination coverage, which may overestimate the effectiveness of this system if people are less compliant with QR sign in and other measures once they are vaccinated.
- This model currently only attributes basic properties to individuals, specifically age, household structure and participation in different contact networks. The model does not account for any other demographic and health characteristics such as socioeconomic status, comorbidities (e.g. non-communicable diseases) and risk factors (e.g. smoking) and so cannot account for differences in transmission risks, testing, quarantine adherence or disease outcomes for different population subgroups.
- The model does not include a geospatial component and so cannot capture geographic clustering of vaccination or infection within some communities.
- The model simulates symptomatic testing by having a parameter for the per day probability of being tested if symptoms are present. This means that the distribution of time from symptom development to testing is binomial, which may differ from the true distribution of time from symptom onset to testing.
- Model parameters are based on best-available data at the time of writing. Results from new studies could change estimates of social mixing, contact networks, adherence to policies, quarantine advice, and disease characteristics (e.g. asymptomatic cases), and these could change these results.

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Appendix: Additional methodological details

The agent-based model *Covasim* models the spread of COVID-19 by simulating a collection of agents representing people. Each agent in the model is characterised by a set of demographic and disease properties:

- Demographics:
  - Age (one-year brackets)
  - Household size, and uniquely identified household members
  - Uniquely identified school contacts (for people aged 5-18)
  - Uniquely identified work contacts (for people aged 18-65)
  - Average number of daily community contacts (multiple settings / contact networks modelled, described below)
- Disease properties:
  - Infection status (susceptible, exposed, recovered or dead)
  - Whether they are infectious (no, yes)
  - Whether they are symptomatic (no, mild, severe, critical; with probability of being symptomatic increasing with age, and the probability of symptoms being more severe increasing with age)
  - Diagnostic status (untested vs tested)

Transmission is modelled to occur when a susceptible individual is in contact with an infectious individual through one of their contact networks. The probability of transmission per contact is calibrated to match the epidemic dynamics observed and is weighted according to whether the infectious individual has symptoms, and the type of contact (e.g. household contacts are more likely to result in transmission than community contacts). Transmission dynamics depend on the structure of these contact networks, which are randomly generated but statistically resemble the specific setting being modelled. The layers included are described below, and the model parameters values are provided for each layer that was included.

Model population

The model population is Melbourne only (5.07 million people), given this represents the overwhelming majority of COVID-19 cases at the time of modelling.

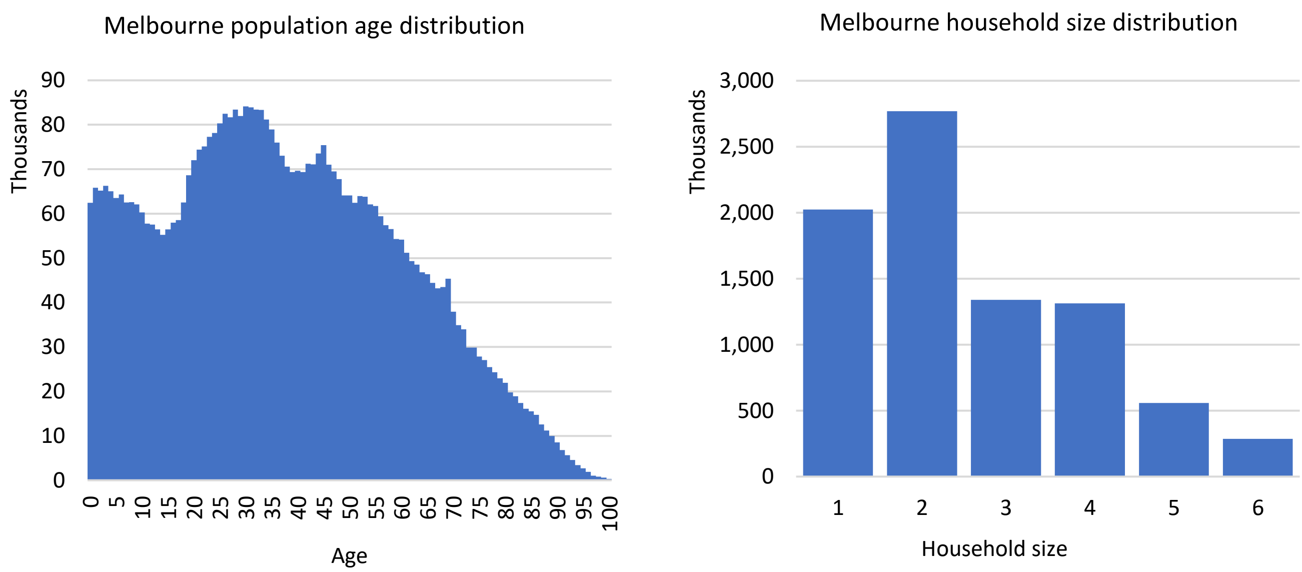

Figure S1: Population age structure and household size distribution [10].

Household contact network: household size and age structure

The household contact network was set up by explicitly modelling households. The households size distribution for Melbourne [10] was scaled to the number required for the number of agents in the simulation. Each person in the model was uniquely allocated to a household. To assign ages, a single person was selected from each household as an index, whose age was randomly sampled from the distribution of ages of the Household Reference Person Indicator in the 2016 Census [10]. The age of additional household members were then assigned according to Australian age-specific household contact estimates from Prem et al. [11], by drawing the age of the remaining members from a probability distribution based on the row corresponding to the age of the index member.

School contact networks

The school contact network was set up by explicitly modelling classrooms. Classroom sizes were drawn randomly from a Poisson distribution with mean 24 [12]. People in the model aged 5-17 years were assigned to classrooms with people their same age. Each classroom had one randomly selected adult (>21 years) assigned to it as a teacher. The result was that the school contact network was approximated as a collection of disjoint, completely connected clusters (i.e. classrooms).

Transmission in schools is influenced by age-specific disease susceptibility, and the age-specific probability of being symptomatic, which influences symptomatic testing interventions. In the model, people under 14 years have an odds ratio of 0.34 for acquiring infection relative to adults [13], and we use Victorian data to determine age-specific probability of being symptomatic, based on the percentage of positive contacts of confirmed cases who were symptomatic when they were tested (during the 2020 epidemic wave).

It was additionally assumed that transmission risks in schools and childcare would be reduced by 50% relative to pre-COVID-19 due to additional distancing, ventilation and other measures in place.

Cohorting in schools (e.g. year levels alternating days) was modelled by reducing the probability of transmission per school contact based on the proportion of time spent in person (e.g. 3/5 for three days per week).

Work contact networks

Two different workplace types were constructed: public facing (e.g. retail, hospitality) and non-public facing. Contact networks for non-public facing workplaces were created as a collection of disjoint, completely connected clusters for the percentage of people aged 18-65 who worked in those settings. The mean size of each cluster was equal to the estimated average number of daily work contacts (Table S1). For the percentage of people aged 18-65 who worked in public facing workplaces, their workplace networks consisted of a completely connected cluster with other work colleagues, as well as each day having a number of random contacts with the community.

Additional contact networks

An arbitrary number of additional networks can be added, but for this analysis we considered those most likely to be subject to policy change. Each network layer required inputs for: the proportion of the population who undertake these activities; the average number of contacts per day associated with these activities; the risk of transmission relative to a household contact (scaled to account for (in)frequency of some activities such as pubs/bars once per week); relevant age range; type of network structure (random, clustered, or specialized [as per schools/workplaces]); and effectiveness of quarantine and contact tracing interventions.

Parameter values for each contact network

Tables S1 and S2 show the parameters that define each contact network in the model. Unless otherwise noted, parameters are derived in [2] from a mix of published and grey literature and a Delphi parameter estimation process. The columns refer to:

- **Network structure type:** Clustered refers to a network structure comprised of disjoint, completely connected groups of contacts. Random refers to individuals being allocated connections to anyone else in the network. Random networks are also dynamic and regenerated each day. Public facing networks are a combination of completely connected clusters for staff, who are then connected to random community members
- **Mean contacts:** The average number of contacts per person in each network. Each person in the model has their individual number of contacts draw at random from a Poisson distribution with these values as the mean. For the social network layer, a negative binomial distribution was used with dispersion parameter 2 to account for a longer tail to the distribution.
- **Mean public-public contacts:** For the percentage of people who participate in an activity, the average number of contacts they have with other members of the public (draw at random from a Poisson distribution with these values as the mean)
- **Mean public-staff contacts:** For the percentage of people who participate in an activity, the average number of contacts they have with staff (draw at random from a Poisson distribution with these values as the mean)
- **Relative transmission risk:** The transmission probability per contact is expressed relative to household contacts, and reflects the risk of transmission depending on behaviour. For example, a casual contact in a public park is less likely to result in a transmission event compared to a contact on public transport. Similarly, the relative transmission risks between staff-staff, public-public and staff-public are characterised for public-facing workplaces.
- **Quarantine effect:** If a person is quarantined, the transmission probability is reduced by this factor. For example, an individual on quarantine at home would likely not work or use public transport, but they may still maintain their household contacts.
- **Population proportion:** Each network will only include a subset of the population e.g. every person has a household, but not every person regularly uses public transport.
- **Age bound:** Each network will only include agents whose age is within this range.
- **Contact tracing probability:** Probability that each contact can be notified in order to quarantine
- **Effectiveness of quarantine and isolation:** When a close contact is asked to quarantine for 14 days, or a confirmed case asked to isolate while they are infected, these parameters represent he effectiveness of at reducing transmission through the specific networks. For example quarantine is assumed to have no impact on household transmission and greater impact on other contacts, reflecting compliance.

Table S1: Contact parameters for each of the networks in the model.

Contact network	Network structure type*	Mean contacts	Mean public-public contacts	Mean public-staff contacts	% of workforce	Relative transmission risk	Relative transmission risk (staff-staff)	Relative transmission risk (public-public)	Relative transmission risk (staff-public)	% of population	Age bound
House	Specialized	4				1.00					
School	Specialized	24				0.25#					5-17
Non-retail work	Specialized	5			0.80	0.28					
Retail work	Public facing	5	8	2	0.11		0.28	0.04	0.04	0.70	12+
Community (general)	Random	1				0.10				1.00	
Places of worship	Clustered	20				0.04				0.11	
Community sport	Clustered	30				0.07				0.34	4-30
Entertainment	Public facing	25	8	2	0.02		0.28	0.01	0.01	0.30	15+
Cafe/restaurant	Public facing	5	8	2	0.02		0.28	0.04	0.04	0.60	12+
Pub/bar	Public facing	5	8	2	0.03		0.28	0.06	0.06	0.40	18+
Public transport	Random	25				0.16				0.11	15+
Public parks	Random	10				0.03				0.60	
Child care	Clustered	20				0.25#				0.55	1-6
Social	Random	6 (disp=2)				0.12				1.00	15+
Aged care	Clustered	12				0.58				0.07	65+

#A 50% reduction was applied to this assuming additional public health interventions are in place when these settings open (e.g. ventilation, distancing).

Table S2: Contact tracing parameters for each of the networks in the model.

Contact network	Assumed contact tracing probability	Assumed effectiveness of quarantine on network	Assumed effectiveness of isolation on network
House	1	0.00	0.80
School	0.95	0.99	0.99
Non-retail work	0.95	0.90	0.90
Retail work	0.95	0.90	0.90
Community (general)	0.1	0.80	0.80
Places of worship	0.5	0.99	0.99
Community sport	0.5	1.00	1.00
Entertainment	0.5	1.00	1.00
Cafe/restaurant	0.5	1.00	1.00
Pub/bar	0.5	1.00	1.00
Public transport	0.1	0.99	0.99
Public parks	0.1	1.00	1.00
Child care	0.95	0.99	0.99
Social	0.75	0.50	0.80
Aged care	0.95	0.80	0.80

Workforce restrictions

Within the model, people aged 18-65 years were classified according to:

- Whether they were working or not (69% were classified as working, based on ABS employment data)
- Industry type, with the workforce classified as:
    - hospitality or entertainment (9% of workers);
    - retail (11%); and
    - other non-retail workers (80%; including 7% construction).

These classifications were used to estimate the impact of policies (Table S5).

Model calibration

For the calibration shown in Figure S2, the model was initialised with a population of 100,000 agents, and the overall transmission risk per contact (which multiplies the transmission probabilities in Table S1 for each layer), the per-day probability of a symptomatic individual seeking testing were varied such that the distribution of model outcomes for diagnoses, hospitalizations and number of tests was centred near the actual epidemic trajectory.

When calibrating, we fit the model transmission parameters under the assumption that the observed epidemic trajectory in July-September 2021 was the most likely outcome, which occurred in all simulations. In reality, it is possible that it was an unlikely/unlucky outcome (i.e. the virus is less infectious than we estimate, but has taken off in subpopulations with higher than average numbers of contacts or higher than average viral loads) , or alternatively, that it could have been worse and was in fact a relatively lucky outcome (i.e. the virus is more infectious than we estimate, and it has happened to seed into subpopulations with lower than average contacts and/or viral loads). Therefore, we sampled over a set of initializations and transmission parameters, and only retained those runs where the seed/transmission parameter combination produced a projection that sufficiently matched the data. We considered the model to be a suitable fit if it was within 20% of the cumulative diagnosed cases.

Figure S2 shows examples of the simulation runs used to estimate parameters for this study. Many initializations were rejected because they diverged from the actual data early on, when case numbers are relatively low and the outcomes of each individual case therefore have a significant impact on the trajectory of the outbreak.

Figure S3 shows the value of the transmission parameter and estimated R_{eff} in the model for the accepted simulations. These simulations were used for forward projection of scenarios.

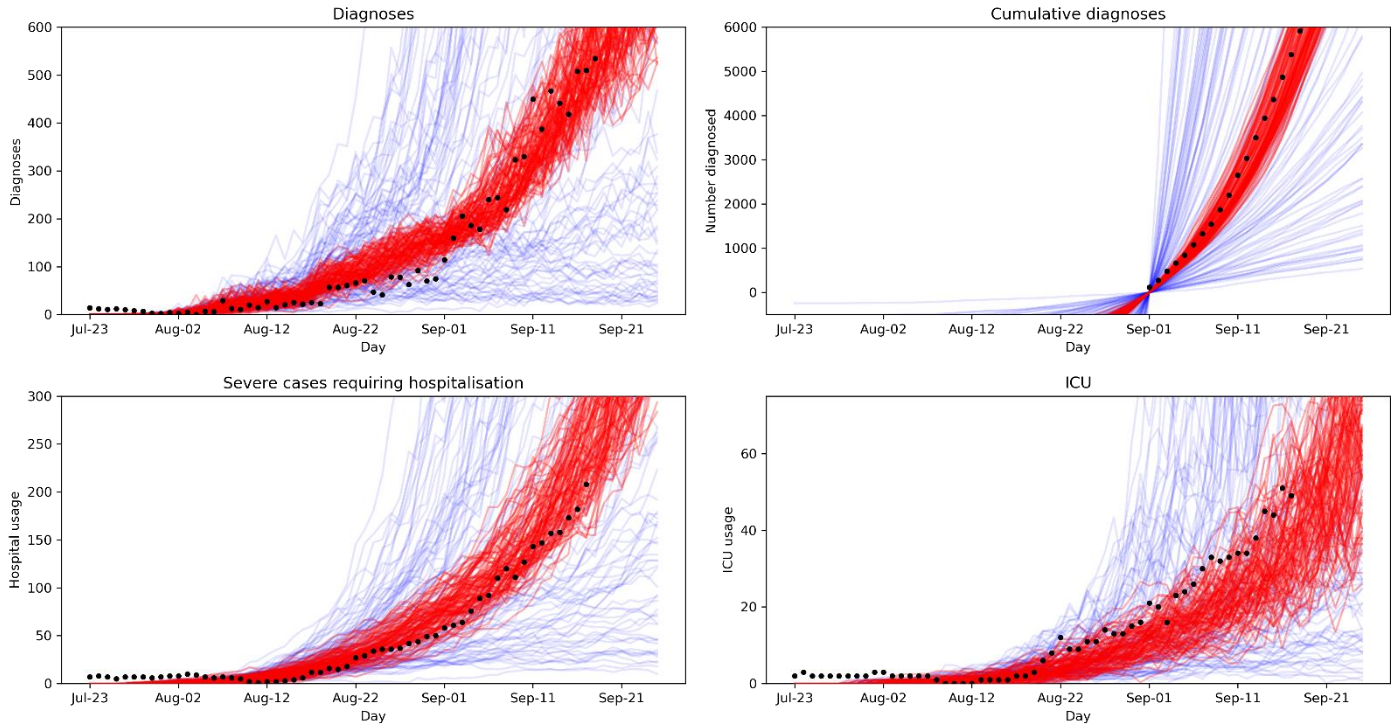

Figure S2: Model calibration to data from July-September 2021. Red lines indicate simulation runs that were maintained and used for this study; blue lines show a representative sample of simulations that were rejected. Cumulative diagnoses have been offset to prioritize calibration to most recent data.

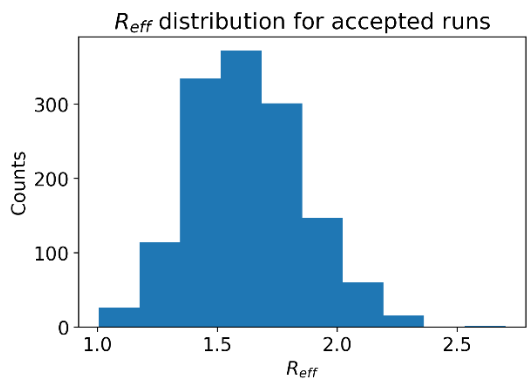

Figure S3: Accepted values for R_{eff}.

Disease prognosis, hospitalization and ICU demand

People in the model who became infected had an age-specific probability of becoming symptomatic or developing severe or critical disease. These probabilities are shown in Table S3 for unvaccinated people, and are modified according to vaccination status (one or two doses, based on vaccine efficacy parameters). Values below have been estimated for wild type variant [14] and then inflated to account for the increased severity of the delta variant (aOR = 2.08) [9].

People who were infected also had an age-specific probability of being in hospital or ICU, based on Knock et al. [15], and then applying the same adjustment for the increased severity of the delta variant. I.e. in the model, the probability of ICU given being in a critical condition is not necessarily 1, for example for people over 70 years.

To estimate peak hospital and ICU demand, these must be paired with estimates of duration of stay (Table S4), which were applied uniformly by age (lacking additional data).

Table S3: Age-specific susceptibility, disease progression and mortality risks for unvaccinated people.

Age bracket	Relative susceptibility*	Pr(symptomatic)^	Pr(severe)#	Pr(critical)#	Pr(hospital)##	Pr(ICU)##	Pr(death)#
0-4	0.34	0.55	0.0020	0.00006	0.0020	0.00006	0.00004
5-9	0.34	0.55	0.0020	0.00006	0.0009	0.00006	0.00004
10-14	0.34	0.55	0.0032	0.00010	0.0032	0.00010	0.00004
15-19	1	0.65	0.0050	0.00017	0.0050	0.00017	0.00004
20-24	1	0.77	0.0190	0.00075	0.0190	0.00075	0.00021
25-29	1	0.77	0.0190	0.00075	0.0190	0.00075	0.00021
30-34	1	0.79	0.0540	0.00216	0.0504	0.00216	0.00067
35-39	1	0.79	0.0540	0.00216	0.0539	0.00216	0.00067
40-44	1	0.79	0.0870	0.00448	0.0597	0.00448	0.00204
45-49	1	0.79	0.0870	0.00448	0.0870	0.00448	0.00204
50-54	1	0.8	0.1840	0.01921	0.1581	0.01921	0.00550
55-59	1	0.8	0.1840	0.01921	0.1840	0.01921	0.00550
60-64	1.24	0.8	0.3020	0.07283	0.2657	0.06932	0.01580
65-69	1.24	0.8	0.3020	0.07283	0.3020	0.07283	0.01580
70-74	1.47	0.85	0.4130	0.16928	0.4130	0.12262	0.04943
75-79	1.47	0.85	0.4130	0.16928	0.4130	0.11996	0.04943
80-89	1.47	0.9	0.4490	0.30496	0.4490	0.03097	0.15830
90+	1.47	0.9	0.4490	0.30496	0.4490	0.03097	0.28663

*Zhang et al. [13] found children <14 had 34% less susceptibility to adults, and people>65 years had 47% increased susceptibility
^Victorian data: percentage of (infected) close contacts who had symptoms when they were tested
#Imperial College age-specific wild type disease prognosis estimates [14]; then adjusting for more severe outcomes with delta, based on a Canadian preprint data (OR = 2.08 being applied to hospitalization, ICU and deaths [9]: the hospital aOR was applied to all probabilities to avoid conditional probabilities becoming greater than 1, and the issue of small sample sizes for ICU and death.
Knock et al. [15] used to calculate age-specific pr(hospitalization or ICU given infection with wild type); adjusted for delta variant as per disease prognosis estimates above. This implies that in the model, only a percentage of people with critical disease end up in ICU, according to age-specific pr(ICU|infection) from Knock et al.

Table S4: Duration of stay in hospital and ICU.

	Severe	Critical	Deaths
Hospital stay (outside ICU)	Mean: 7.8 days Standard deviation: 8.3 days Lognormal distribution Reference: FluCAN 2020 (CDNA COVID Epi Report August 30 2020)	Mean: 1.5 days Standard deviation: 2.0 days Lognormal distribution Reference: Chen et al. [16]	Mean: 1.5 days Standard deviation: 2.0 days Lognormal distribution Reference: Chen et al. [16]
ICU stay		Mean: 11.3 days Standard deviation: 27.9 days Lognormal distribution	Mean: 16.1 days Standard deviation: 22.6 days Lognormal distribution

		Reference: FluCAN 2020 (CDNA COVID Epi Report August 30 2020) Fitted from median: 4 days, IQR 2-11	Reference: FluCAN 2020 (CDNA COVID Epi Report August 30 2020) Fitted from median: 9 days, IQR 5-19

Policies

The policies being modelled apply to different contact networks in the model, and have been derived through calibration to past epidemic outbreaks in Victoria and NSW [2-4].

Table S5: Policy impacts in the model.

Policy area	Policy	Impact in model
Childcare	Authorized or vaccinated parents only	Reduce transmission by 60%. Based on 40% reduction in enrolment (authorized only component), 50% of remaining children are excluded with the vaccination policy, and an overall assumed additional 50% reduction due to NPIs ([0.6 + 0.4*0.5] *0.5).
Schools	Closed	Attendance reduced to 9% for vulnerable children
	Open with NPIs	Full attendance and 50% reduction in transmission risk in school setting. Applied independently per year level.
	Cohorting	When this policy is in place, the probability of transmission per school contact based on the proportion of time spent in person (e.g. 3/5 for three days per week). Applied to specific year levels.
Café/restaurant	Take-away only	30% of venues closed; venue capacity reduced to 0; 35% reduction in transmission risk per contact
	Outdoor only with 4sqm rule	80% reduction in number of contacts per person; 50% reduction in transmission risk per contact
	4 sqm rule	50% reduction in number of contacts per person
Pub/bar	Take-away only	30% of venues closed; venue capacity reduced to 0; 35% reduction in transmission risk per contact
	Outdoor only with 4sqm rule	80% reduction in number of contacts per person; 50% reduction in transmission risk per contact
	4 sqm rule	50% reduction in number of contacts per person
Retail	Essential only	20% of retail closed; 40% reduction in contacts for retail work that remains open
	4 sqm	50% reduction in contacts
Places of worship	Closed	Contacts in setting reduced to zero
	Outdoor only	80% reduction in transmission risk per contact
	4 sqm	30% reduction in transmission risk per contact
Community sport	Closed	Contacts set to zero
Outdoor gatherings	2 for exercise	50% reduction in transmission risk in social and public park networks
	<10 outdoors + no home visitors	20%, 40% and 40% relative reductions in transmission risk in community, social and public park networks
	<50 outdoors + 5 visitors at home	20% reduction in community and social contacts, 10% reduction in public park contacts
Non-retail work	Work from home if possible, construction closed	20% of workforce removed from work network; 40% relative reduction in transmission risk per work contact; 33% reduction in transmission risk per transport contact and community contact; 10% increase in household transmission risk
	Work from home if possible, construction open	13% of workforce removed from work network; 40% relative reduction in transmission risk per work contact; 20% reduction in transmission risk per transport contact and community contact; 10% increase in household transmission risk
Entertainment	Closed	Contacts turned off
	Outdoor only, 10 per group	70% reduction in number of contacts per person; 80% reduction in transmission risk per contact
	4 sqm	70% reduction in number of contacts per person
Mobility	5km	30-70% reduction on community transmission
	10km	20% and 50% reduction in community and transport transmission risks
Masks	Mandatory	30% reduction in transmission risk in work, entertainment; transport, aged care settings; 25% reduction in community, social, public parks and places of worship; 20% reduction in schools; 10% reduction in cafes, restaurants pubs and bars
	Indoors only	30% reduction in transmission risk in work, entertainment; transport, aged care settings; 25% reduction in places of worship; 20% reduction in schools; 10% reduction in cafes, restaurants pubs and bars

Median of the peak of each simulation versus the peak of the median line

Figure S4 illustrates how the peaks of individual simulations (red dots) occur on different calendar dates, which means that the median at a given time point (blue line) does not necessarily reflect the median peak value across all simulations (red line).This is why the solid median line in the results figures may be lower that the reported values in the results table. The figures should be considered as illustrative and the values in the tables the projected outcomes.

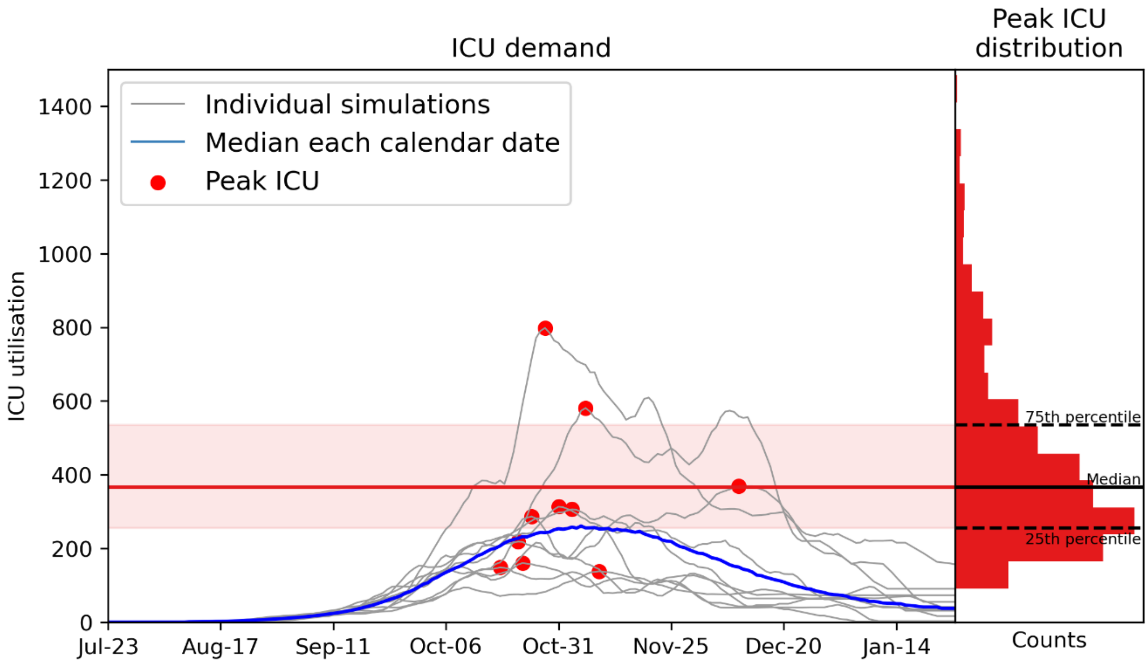

Figure S4: Median line over time, versus peaks of individual simulations.