A study of the effectiveness of travel restrictions in Japan

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Prepared for ACI Asia-Pacific

Oxera and Edge Health

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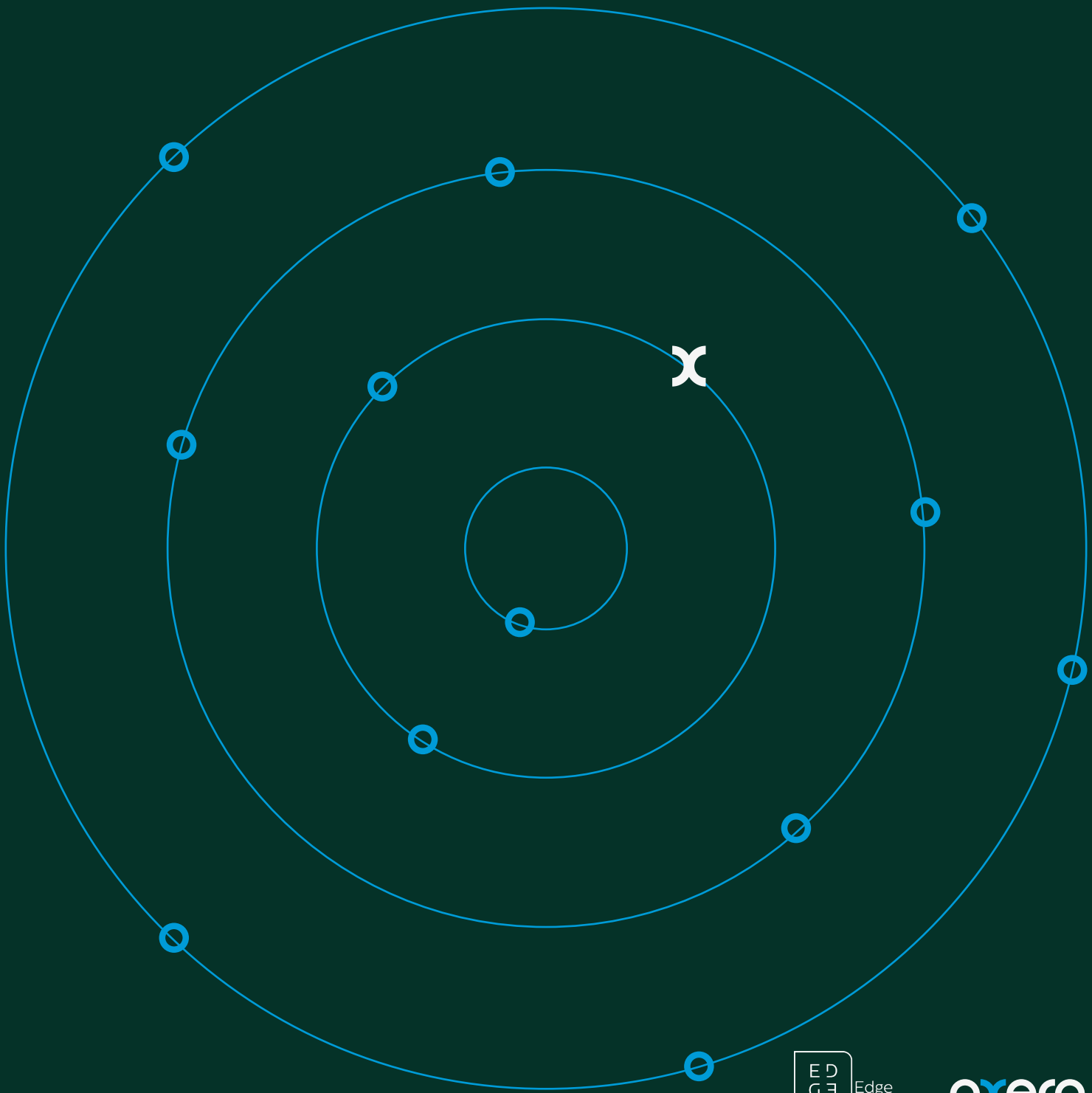


Edge Health

oxera

Executive summary

There have been extensive travel restrictions in place across the Asia-Pacific region over the last two years, ranging from mandatory quarantines in designated facilities to pre-departure testing and on-arrival testing.

In Japan, travel restrictions were introduced at the start of the pandemic in March 2020. They began with 14-day quarantine requirements for passengers entering from South Korea and China, which soon extended to a ban on passengers entering from 21 European countries and then to most countries. Since then, travel to/from Japan has been limited to a daily cap, with requirements for pre-departure testing, on-arrival testing, and/or quarantine.

On 1 June 2022, the Japanese government announced that countries will be split into three categories, which will determine the relevant travel restrictions for passengers when entering Japan. Travellers arriving from red countries, for example, will be required to take both a pre-departure test 72 hours before travel and an on-arrival test, and spend three days in quarantine at a designated government facility regardless of their vaccination status. The travel restrictions for passengers from yellow countries will depend on vaccination status—those with three doses of an approved vaccine will be required to take a pre-departure test, but will be exempt from on-arrival testing and quarantine.[1] Passengers arriving from countries in the blue category will only be required to take a pre-departure test. The Japanese government has also increased the number of arrivals permitted from 10,000 to 20,000 per day, and from 10 June tour groups will be allowed to enter the country with quarantine restrictions also depending on the risk categorisation of the origin country. Despite these consistent and stringent travel restrictions, Japan has experienced waves of COVID-19, particularly in January 2022 due to the Omicron variant.

While the current wave of infections associated with the Omicron variant is subsiding, new Variants of Concern (VOCs) are likely to continue to emerge. However, over two years on from the start of the pandemic, there is a question about whether implementing travel restrictions to protect domestic populations against COVID-19 is a useful and proportionate approach.

Indeed, analysis shows that travel restrictions have failed to prevent the spread of COVID-19.[2] Specifically, the International Health Regulation Emergency Committee of the World Health Organization (WHO) has highlighted the failure of travel restrictions to limit the importation of VOCs. The WHO noted that:[3]

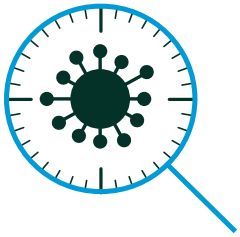
> The failure of travel restrictions introduced after the detection and reporting of Omicron variant to limit international spread of Omicron demonstrates the ineffectiveness of such measures over time. Travel measures (e.g. masking, testing, isolation/quarantine, and vaccination) should be based on risk assessments and avoid placing the financial burden on international travellers […].

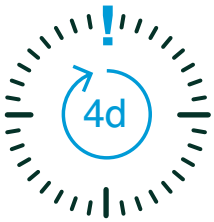
[1] Travellers coming from countries and regions listed in the yellow category who do not have a booster vaccine must take a Covid-19 test on arrival and spend seven days in home quarantine. However, if they take a voluntary test on day 3 of quarantine and get a negative result, they will be allowed to leave quarantine.
[2] For example, see: Oxera and Edge Health (2022), 'A study of the effectiveness of travel restrictions in the EEA', prepared for ACI Europe and IATA, 24 February; Oxera and Edge Health (2022), 'A framework for considering the impact of air travel restrictions on the UK', prepared for Manchester Airports Group and Airlines UK, January.
[3] World Health Organization (2022), 'Statement on the tenth meeting of the International Health Regulations (2005) Emergency Committee regarding the coronavirus disease (COVID-19) pandemic', 19 January, https://www.who.int/news/item/19-01-2022-statement-on-the-tenth-meeting-of-the-international-health-regulations-(2005)-emergency-committee-regarding-the-coronavirus-disease-(covid-19)-pandemic.

One of the key measures to limit the impact of any future wave of COVID-19 is vaccination. As Japan has one of the most highly vaccinated populations in the world, the risk of having a large COVID wave is significantly reduced. In particular, removing travel restrictions is unlikely to lead to spikes in serious cases that require hospitalisation, which is increasingly being seen as a more important factor than the gross number of cases. This has been demonstrated by other countries in the region that have similarly highly vaccinated populations (or even less highly vaccinated in some cases) that have opened up to international travel, creating economic benefits without creating risks to public health.

As we look to a world where COVID-19 is endemic, it is relevant to consider the role of air passenger travel restrictions in limiting the importation of COVID-19, particularly as a result of new VOCs.

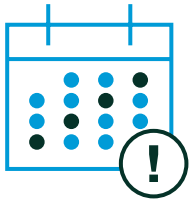
There is unlikely to be a demonstrable benefit associated with introducing travel restrictions in response to new variants. This is consistent with experience since the beginning of the pandemic which indicates that it is difficult to identify a variant as a VOC sufficiently quickly to be able to introduce travel restrictions that have a meaningful impact.





Even if travel restrictions were pre-emptively introduced, or could be put in place on the day that the variant is first imported, they would not have an impact on limiting the peak of cases,[4] and would only delay the peak by a maximum of four days with a pre-departure PCR test or ten days with pre-departure and on-arrival PCR tests. Japan introduced measures three weeks after Omicron was likely first imported into the country, by which point the restrictions no longer had any impact on the trajectory of Omicron.[5]

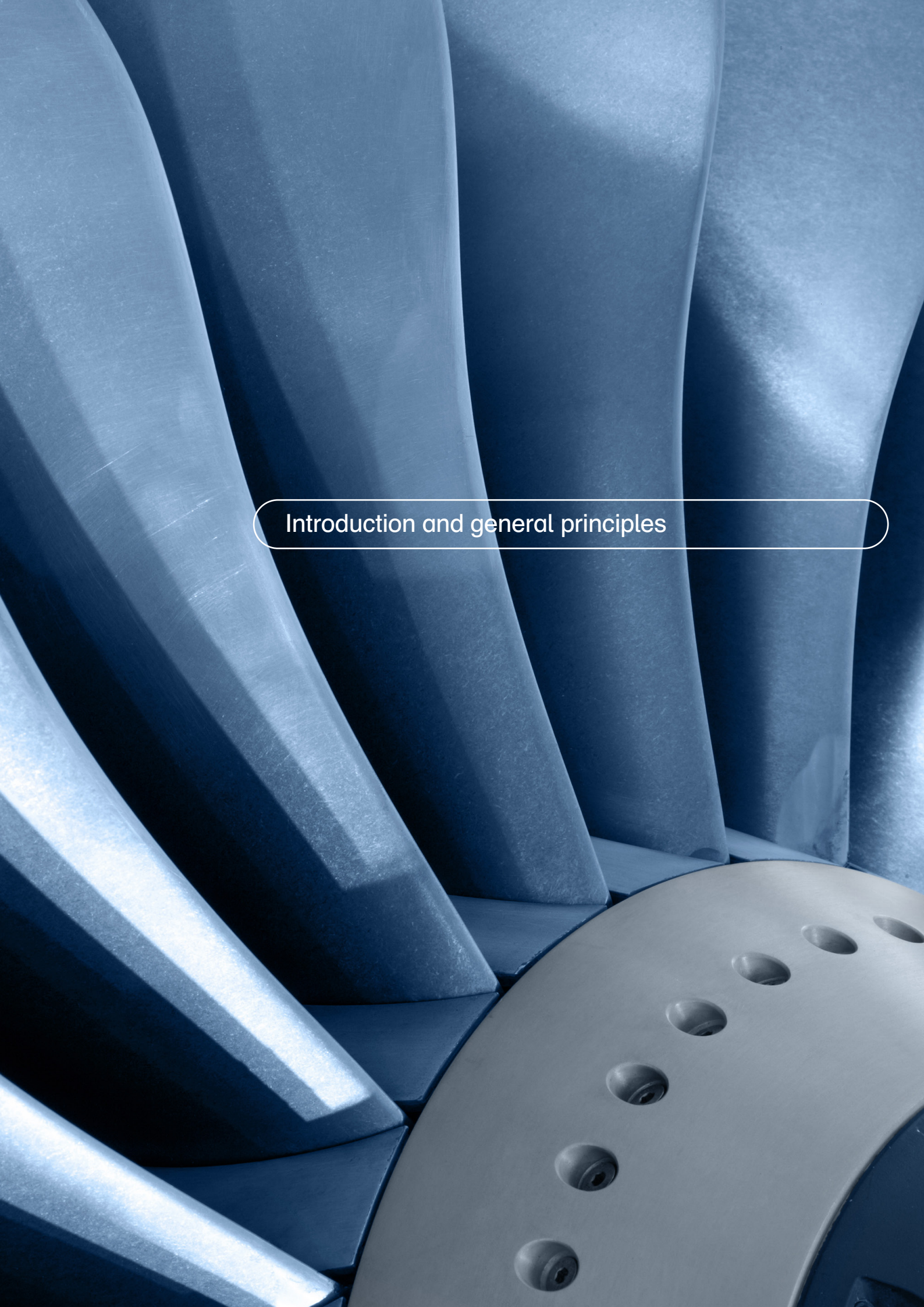
The effectiveness of travel restrictions is further reduced when a variant is more infectious. If the introduction of travel restrictions is delayed by even one week, the benefit of travel restrictions in terms of delaying the peak of COVID-19 cases declines, to a maximum of three days from the day that the variant is first imported.



[4] Once there is no longer an active vaccination campaign, travel restrictions do not have any impact on the height of the peak of cases. This is consistent with other research, see https://www.degruyter.com/document/doi/10.1515/em-2020-0042/html?lang=en

[5] Based on retrospective sequencing, Omicron was identified as early as 8 November in South Africa and internationally.

Overview



Introduction and general principles

Introduction

There have been a range of international travel restrictions in place across the Asia-Pacific region since the start of the pandemic. Many of the restrictions have been much stricter than those in place in a number of other regions, but individual countries have implemented different restrictions from one another in response to the same set of circumstances. These restrictions have also changed over time within a given country—e.g. from mandatory quarantine, to pre-departure PCR tests, to antigen tests upon arrival.

Successful vaccination campaigns, natural immunity, and improved treatments such as antivirals mean that many Asia-Pacific countries have removed or are significantly reducing travel (and local) restrictions even as COVID-19 is still spreading. For example, Vietnam started welcoming international travellers in March 2022, and countries such as Singapore and Malaysia have started to relax travel restrictions. Importantly, these removals of travel restrictions have not been accompanied by new waves of COVID-19. At the same time, Japan still has significant travel restrictions in place, albeit there are discussions about lifting (some of) these over the coming months.

However, the experience with Omicron shows that countries are quick to introduce travel restrictions once a variant is identified as a VOC,[6] and then slow to remove them. Indeed, Japan strengthened its travel restrictions after Omicron was identified as a VOC, despite evidence showing that travel restrictions have not been effective at slowing the spread of Omicron, and the significant costs of such restrictions for passengers, the aviation sector, and the economy.

Looking forward, there are likely to be new VOCs. The key question, therefore, is what role travel restrictions can play in reducing the spread of COVID-19, based on the data and lessons of the last two years.

It is in this context that ACI Asia-Pacific has asked Oxera and Edge Health to analyse the impact that travel restrictions could have going forward. In particular, we have analysed a number of different scenarios around the importation of VOCs and future waves of COVID-19 to help consider:[7]

- the extent to which travel restrictions affect the speed and peak of the spread of COVID-19 as a result of a new variant;
- the impact of different types of travel restrictions—e.g. no testing or quarantine, pre-departure testing only, and both pre-departure and on-arrival testing;
- the trigger points for bringing in, as well as removing, testing requirements to deal with new VOCs—i.e. the critical point at which introducing travel restrictions could have an impact and the point at which there would be a critical mass of a VOC domestically such that travel restrictions are no longer relevant.

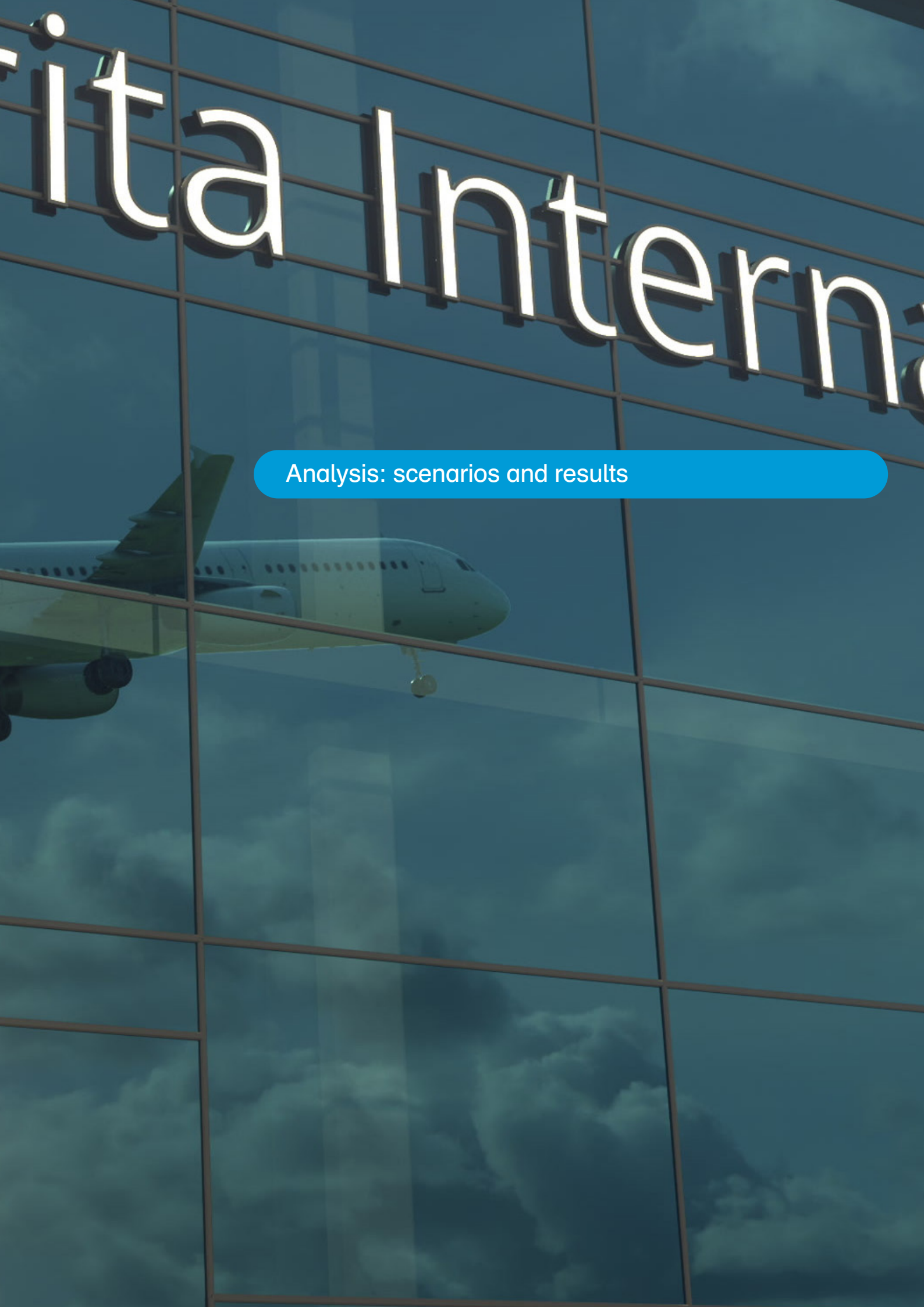
[6] There is generally a delay between variants first being sequenced and then identified as a VOC. This means that even if travel restrictions are put in place soon after a variant is identified as a concern, it is likely that cases will have already been seeded at that stage.
[7] This analysis builds on previous analysis undertaken by Oxera and Edge Health over the last year. For example, see Oxera and Edge Health (2022), 'Impact of travel restrictions on Omicron in Italy and Finland', prepared for ACI Europe and IATA, 26 January.

Our analysis will help provide information about the benefits of travel restrictions from a public health perspective that can be compared with the costs that such restrictions impose on the economy.

General principles for imposing travel restrictions

In order to determine appropriate travel restrictions going forward, it is important to consider the objective of such restrictions. Any restrictions imposed should aim to minimise economic disruption. This includes all potential issues that could arise as a result of seeding new VOCs, such as the impact of widespread infection on health services, as well as the disruption caused to the economy. In line with this objective, it is relevant to consider the following key principles.

- Travel restrictions should be removed once seeded cases exceed the level beyond which such restrictions would make a material difference to the trajectory of infections.
- Travel restrictions should be imposed only if they can have a meaningful impact on the peak and/or timing of cases; otherwise they should not be imposed at all.
- The costs of imposing any restrictions should be balanced against the benefits.
- Given the incremental cost of restrictions, they should be targeted as much as possible.



Analysis: scenarios and results

Scenarios modelled

We have modelled a number of scenarios to consider the impact of future air travel restrictions. The modelling includes three scenarios that reflect the most likely outcomes over the next several months (i.e. short- and medium-term scenarios) where variants are more infectious than Omicron or are able to evade vaccines.

The modelling also considers a potential scenario for the longer term. In this scenario, less infectious variants could become dominant. However, it is difficult to predict what will happen in the longer term (e.g. natural immunity could be greater, meaning even less infectious variants could become dominant; or natural immunity could wane such that Omicron becomes dominant again), so it will be important to consider the longer-term picture again as more data becomes available.

Each scenario has been modelled for the case where: traffic is back to 60% of 2019 levels, to consider the impact when traffic returns to more normal volumes ('high volume scenario');[8] international traffic volumes remain at their current level of 3% of 2019 volumes ('low volume scenario'). In the Appendix, we provide a sensitivity analysis that considers the impact of travel restrictions if natural immunity wanes going forward and booster programmes are being rolled out.

We look at three different types of travel requirements: 1) pre-departure PCR testing; 2) pre-departure and on-arrival PCR testing;[9] 3) no testing or quarantine regime in place. In particular, we consider the first and second of these, as these are the current testing requirements in Japan depending on an individual's vaccination status and their country of origin.

We note that on-arrival testing at the airport is unlikely to be feasible when traffic returns to 60% of 2019 levels due to operational constraints. In addition, there would be significant costs associated with dual-testing (or indeed any testing regime) when passenger volumes reach this level. However, we have modelled this scenario for illustrative purposes to understand the potential impacts of travel testing on future variants of concern over the next several months when traffic recovers more significantly.

[8] We note that as of March 2022, IATA has forecast that traffic to/from/within Asia Pacific will only reach 68% of 2019 levels in 2022. We assume that Japan will be below the average due to the continuation of strong travel restrictions. This modelling addresses the impact of variants imported. We therefore only consider international air passenger traffic (passenger volumes coming from countries outside of Japan) in both the low and high volumes cases.
[9] We consider an on-arrival test the first day an individual lands in Japan, i.e. on Day 0. This does not necessarily need to be at the airport.

Scenarios considered

Scenario	Rt of scenario*	Description of scenario	Travel restrictions modelled
		Short/medium term	
Scenario 1	3.25	**Omicron +**: variant slightly (1.25 times) more infectious than Omicron once 57% of the population has some vaccine immunity and 7% of the population has some natural immunity to Omicron.	(i) no testing or quarantine (ii) pre-departure PCR test (72hrs) (iii) pre-departure PCR test (72hrs) and on-arrival test
Scenario 2	3.66	**Vaccine escape variant**: same infectiousness as Omicron but twice the immune escape, and therefore an Rt 1.4 times more infectious than Omicron once 57% of the population has vaccine immunity and 7% of the population has some natural immunity to Omicron.	
Scenario 3	6.51	**Omicron ++**: variant significantly (2.5 times) more infectious than Omicron once 57% of the population has vaccine immunity and 7% of the population has some natural immunity to Omicron.	
		Longer term	
Scenario 4	3.16	**Omicron -**: variant slightly (1.25 times) more infectious than Omicron once 57% of the population has vaccine immunity and 10% of the population has some natural immunity to Omicron.	

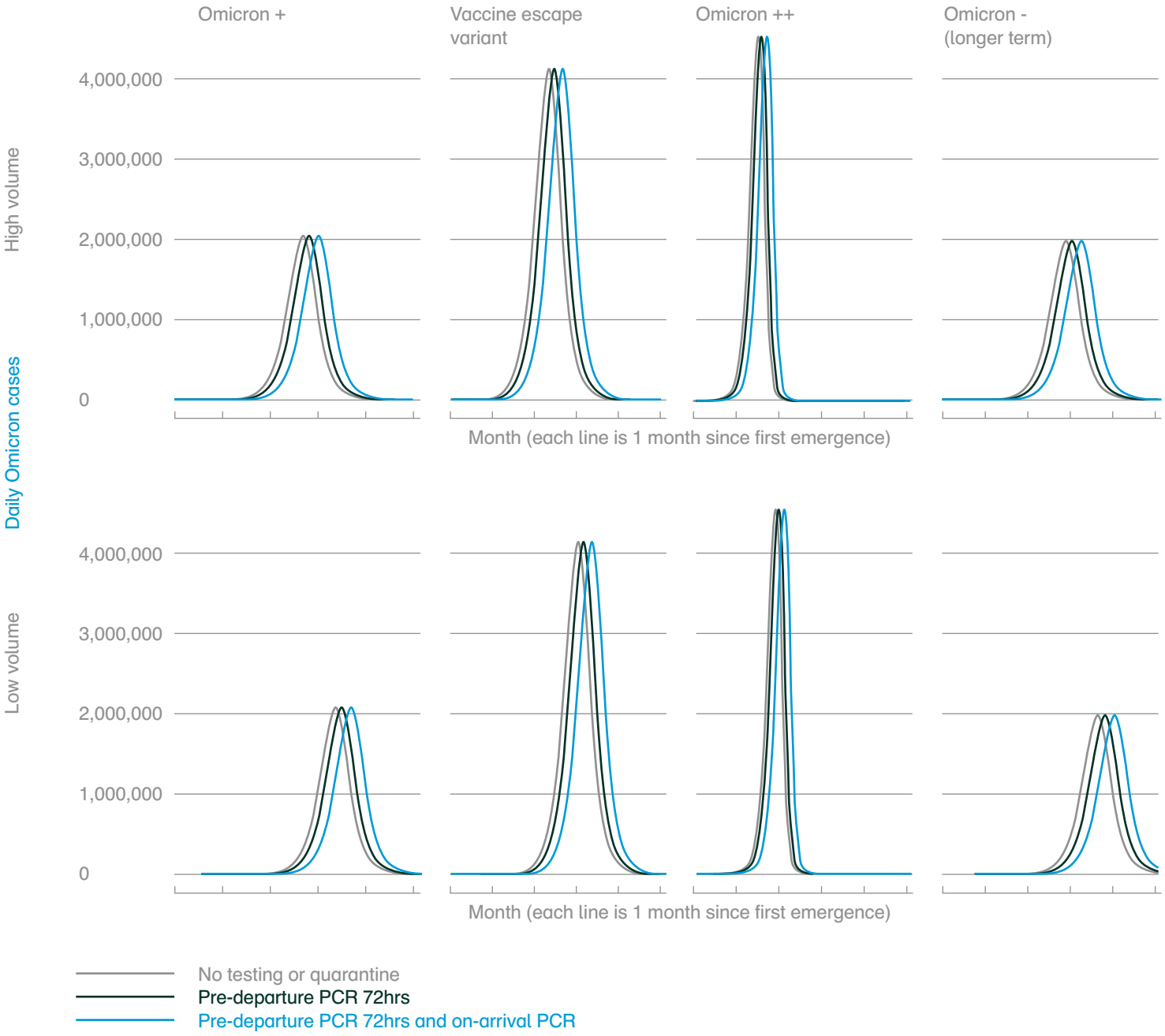
Note: * Rt is when the variant is first seeded. We have assumed that mask wearing continues to be in place.

Results

Air travel restrictions do not affect the height of the peak

Introducing air passenger testing does not affect the height of the peak of cases, relative to not having any restrictions in place. Similarly, the volume of air passengers does not impact the height of the peak of cases. [10]

Booster vaccine rolled out



[10] Once an active vaccination campaign is complete, travel restrictions and traveller volumes no longer have any impact on the height of the peak of cases. This is because peak height is determined by the size of the susceptible population when the variant is first imported. In the absence of a large-scale vaccination campaign, the number of people who are at risk of catching the virus is constant. In this situation, international air passenger volumes can impact the timing of the peak, but they do not impact the peak height. This result is consistent with other research—for example, see: https://www.degruyter.com/document/doi/10.1515/em-2020-0042/html?lang=en. We use SEIR modelling for this study and note that the use of SEIR models (and compartmental models more generally) is a well-established method in epidemiological modelling. For example, see: https://bmjopen.bmj.com/content/12/3/e052681 https://www.thelancet.com/pdfs/journals/lanpub/PIIS2468-2667(20)30073-6.pdf https://www.nature.com/articles/s41598-021-86873-0.

There is a small impact of air passenger testing on the timing of the peak; however, as the variant gets more infectious, the impact of travel restrictions on the delay in the peak decreases.

The table below shows the impact of variant infectiousness on the delay of the peak when travel volumes are high (i.e. 60% of 2019 levels). Variants are ordered from least to most infectious. The imposition of air passenger testing leads to between a four- and a ten-day delay in the peak of cases, depending on whether there is only a pre-departure test in place or also an on-arrival test. This delay is measured from the day that the variant is first imported, which is likely to precede a variant being identified as a concern.

Travel restriction	Scenario	Delay in peak relative to no testing and quarantine (days)
Pre-departure PCR 72hrs—60% of 2019 volumes	Omicron -	4
	Omicron +	4
	Omicron ++	2
	Vaccine escape variant	3
Pre-departure PCR 72hrs and on-arrival PCR—60% of 2019 volumes	Omicron -	10
	Omicron +	10
	Omicron ++	5
	Vaccine escape variant	8

Impact of delaying travel restrictions on the timing of the peak

As variants become more infectious according to the scenarios we have modelled, it becomes more difficult to impose travel restrictions that can have an impact on the timing of the peak of cases. The tables below show how the delay of the peak depends on the number of days it takes to put restrictions in place. For example the first table shows for Omicron ++, if pre-departure tests were put in place four days after the variant was first imported, there would be no benefit in delaying the peak and the travel restrictions would actually have no impact. The second table shows that if pre-departure and on-arrival testing were introduced after six days, there would no longer be any benefit to having such restrictions in place. Indeed, if travel restrictions are delayed by just three days, then even if dual-testing is applied, there will be less than a one week benefit in delaying the peak across all modelled scenarios. It took Japan about three weeks from the time that Omicron was first sequenced and likely first imported into the country (i.e. on 8 November 2021) to introduce travel restrictions, indicating that the restrictions put in place had little to no impact.

The tables below show the impact of variant infectiousness on the delay of the peak when travel volumes are high (i.e. 60% of 2019 levels). Variants are ordered from least to most infectious. The scenario where Day 0 travel restrictions are introduced can be considered akin to having pre-emptive travel restrictions in place.

Delay of peak with pre-departure PCR testing (72 hours before flight)

	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Omicron -	4	4	3	3	2	2	2	2
Omicron +	4	3	3	3	2	2	2	2
Omicron ++	2	1	1	1	0	0	0	0
Vaccine escape variant	3	3	2	2	2	1	1	1

Delay of peak with pre-departure and on-arrival PCR testing (72 hours before flight and on-arrival testing at Day 0)

	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Omicron -	10	8	7	6	5	4	4	3
Omicron +	10	8	6	5	5	4	3	3
Omicron ++	5	3	2	1	1	1	0	0
Vaccine escape variant	8	6	5	4	3	3	2	2

Conclusions

Conclusions

Air travel restrictions do not affect the height of the peak but could delay the peak by a few days if they are introduced on the day the variant is first imported

Our analysis indicates that travel restrictions have no impact on the height of the peak, consistent with research by other epidemiologists.[11] Travel restrictions could delay the peak of cases by a maximum of four days with a pre-departure test or ten days in certain circumstances with a pre-departure and an on-arrival test. At this stage in the pandemic, where governments already have procedures in place for managing Covid-19, the benefit of such a delay is likely to be limited. This is also the case only if restrictions could be introduced on the same day that a variant is imported and therefore likely before it is actually identified as a VOC.

Any benefits of air travel restrictions diminish quickly over time

Each additional day of delay leads to a reduction in the effectiveness of travel restrictions. If restrictions are not imposed until one week after the variant is imported, there is at most three days' benefit to introducing such restrictions in terms of the trajectory of COVID-19 infections, even if both pre-departure and on-arrival tests are introduced. It is notable that it took Japan approximately three weeks after the variant was first imported to introduce travel restrictions in response to Omicron.

Ongoing restrictions will have a significant impact on the economy

Experience since the start of the pandemic indicates that it takes time to become aware of a variant, and then to identify it as a concern, such that putting policies in place sufficiently quickly is likely to be extremely difficult to be able to have a meaningful impact on the spread of COVID-19. The minimal benefit of such restrictions need to be traded off against the significant direct and indirect costs to the economy that they impose.

Monitoring the situation for the long term is important

In the longer term, if a less infectious variant is able to become dominant, travel restrictions may have limited benefits. However, it is difficult to determine potential scenarios beyond the short/medium term, and it would therefore be important to reconsider the restrictions for the period beyond the next several months at a later stage.

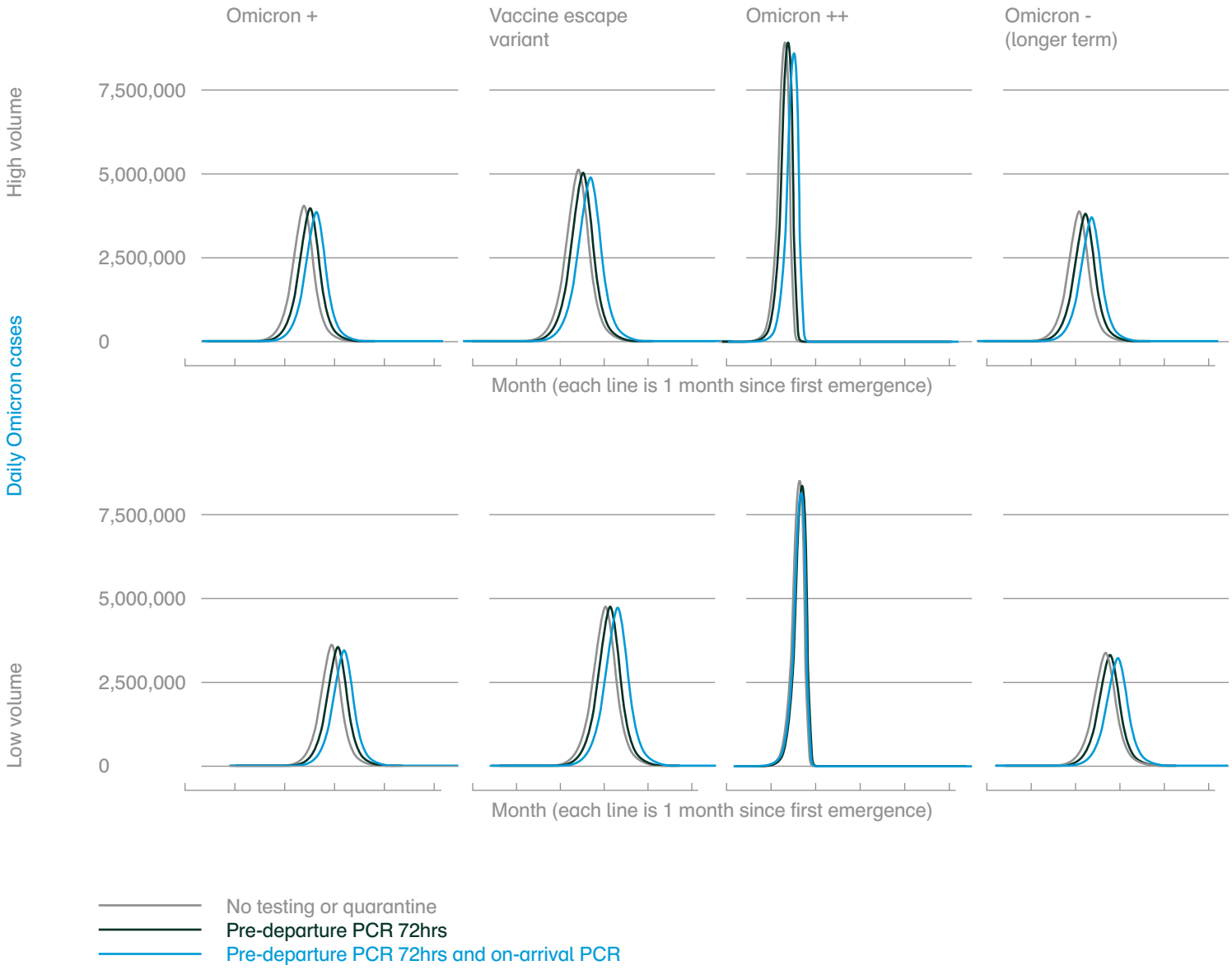
[11] For example, see: https://www.degruyter.com/document/doi/10.1515/em-2020-0042/html?lang=en.

Appendix

A1.1 Sensitivity: when there is an ongoing vaccination roll-out

If there is an ongoing vaccine roll-out (e.g. due to waning immunity), travel restrictions can have a small impact on the peak of cases and can delay the peak by a few days, particularly when travel volumes are high.

Booster vaccine still being rolled out



However, as the variant gets more infectious, the impact of travel restrictions on the delay in the peak decreases, even when vaccines are still being rolled out.

The table below shows the impact of variant infectiousness on the height and delay of the peak when boosters are still being rolled out and travel volumes are high (i.e. 60% of 2019 volumes). Variants are ordered from least to most infectious.

Travel restriction	Scenario	Delay in peak relative to no testing and quarantine (days)	Reduction in peak relative to no testing and quarantine[13]
Pre-departure PCR 72hrs—60% of 2019 volumes	Omicron -	2	2%
	Omicron +	2	2%
	Omicron ++	2	0%
	Vaccine escape variant	3	1%
Pre-departure PCR 72hrs and on-arrival—60% of 2019 volumes	Omicron -	7	6%
	Omicron +	7	5%
	Omicron ++	5	2%
	Vaccine escape variant	8	2%

[13] Reduction calculated as $\Delta z=(z-z_0)/z_0$ where z is the peak number of cases for the current modelling scenario and Z_0 is the peak number of daily cases when no travel restrictions are used.

A1.2 Traffic sensitivity: traffic at 3% of 2019 levels

The tables below display the impact of variant infectiousness on the delay of the peak when there are lower travel volumes (i.e. 3% of 2019 levels). The variants are ordered from least to most infectious.

Booster vaccine rolled out

Travel restriction	Scenario	Delay in peak relative to no testing and quarantine (days)
Pre-departure PCR 72hrs—3% of 2019 volumes	Omicron -	4
	Omicron +	4
	Omicron ++	2
	Vaccine escape variant	3
Pre-departure PCR 72hrs and on-arrival PCR—3% of 2019 volumes	Omicron -	10
	Omicron +	10
	Omicron ++	5
	Vaccine escape variant	8

Booster vaccine still being rolled out

Travel restriction	Scenario	Delay in peak relative to no testing and quarantine (days)	Reduction in peak relative to no testing and quarantine
Pre-departure PCR 72hrs—3% of 2019 volumes	Omicron -	3	2%
	Omicron +	2	2%
	Omicron ++	2	0%
	Vaccine escape variant	3	1%
Pre-departure PCR 72hrs and on-arrival PCR—3% of 2019 volumes	Omicron -	7	3%
	Omicron +	7	3%
	Omicron ++	5	3%
	Vaccine escape variant	8	2%

A1.3 Modelling approach

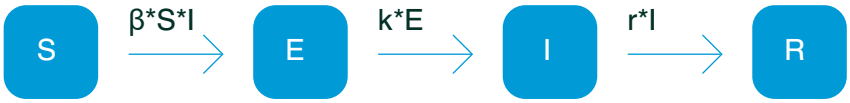
One measure of how easily a virus is spread from one person to another is the virus' reproductive ratio (called its 'R' value). Rt represents the average number of secondary infections that will result from an initial infection at a given time.

The effective reproduction number is determined by the following:

- R0, basic reproduction number: the average number of secondary infections resulting from an initial infection in a fully susceptible population.
- Vaccination-induced immunity: the proportion of the population prevented from being infected by the virus (either symptomatically or asymptomatically) and hence prevented from spreading the virus as a result of being vaccinated.
- Natural immunity: the proportion of the population prevented from being infected by the virus (either symptomatically or asymptomatically) and hence prevented from spreading the virus due to previous exposure to the virus
- Behavioural patterns: different patterns in interactions may hinder the spread of a virus. For example, reduced social interactions, social distancing and masks will contribute to reducing the spread.

If Rt > 1, the virus will spread in a population.

In a basic SEIR model, the entire population is split into groups corresponding to the S (susceptible), E (exposed), I (infected), R (removed) states.

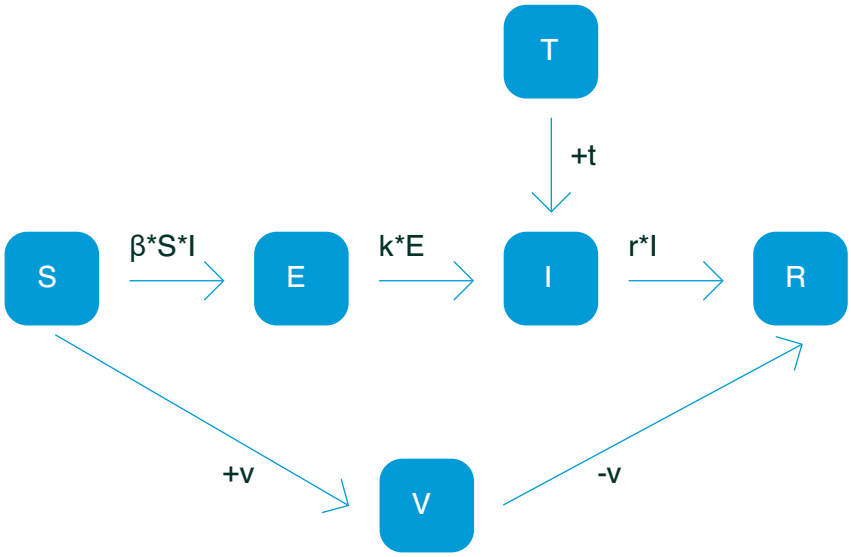


Where:
- β is the parameter for infectivity;
- r is the constant per capita recovery rate;
- k is the constant per capita progression from exposed to infectious rate.

In the basic model, it is assumed that:
- no one is added to the susceptible group, since births and immigration are ignored;
- the only way an individual leaves the susceptible group is by becoming exposed/infected;
- a fixed fraction of the infected group recovers (or dies) every day and is immune to the disease.

SEIR modelling including vaccinations and imported cases

Our model adds additional groups to the SEIR model, corresponding to the population immune from vaccinations and travel-related cases. See details below.



Where:

- β is the parameter for infectivity;
- r is the constant per capita recovery rate;
- k is the constant per capita progression from exposed to infectious rate.
- v is the change in vaccine induced immunity in the population;
- t is daily travel-imported cases.

We assume that:

- No one is added to the susceptible group, since births and immigration are ignored. Infectious travellers enter the infected group directly.
- The only way an individual leaves the susceptible group is by becoming infected or vaccinated.
- A fixed fraction of the infected group recovers (or dies) every day and is immune to the disease.

A1.4 Assumptions

Assumptions on travel volumes and air passenger prevalence

Model input	Description	Value	Source
Median infectious days an air passenger spends in their destination	Without quarantine and testing schemes, when a passenger is infected in another country, they will spend some of their infectious days in their country of departure and some in their country of arrival. Using a simulation model based on a paper from LSHTM, we estimated that the median number of infectious days that a passenger will spend in their country of arrival is three.	3 days	Oxera and Edge Health (2021), 'Effectiveness of dual-testing schemes for air passengers'. For LSHTM's work see: Clifford et al. (2020), 'Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers', 25 July.
Air passenger volumes	We use the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MILT) data on international passenger volumes for April to July 2019 to approximate future air traffic volumes. We model two scenarios: 3% of 2019/20 volumes and 60% of 2019/20 volumes. We assume that most passengers are completing round trips, so passenger volumes are divided by two to get inbound passengers.	We model two scenarios: 3% of 2019/20 volumes and 60% of 2019/20 volumes	Ministry of Land, Infrastructure, Transport and Tourism (MILT)
Air passenger COVID-19 prevalence	To recreate future fictional scenarios that are comparable to Omicron, we model future VOCs (Omicron -, Omicron +, Omicron ++, Vaccine escape variant) assuming COVID-19 prevalence is the same as towards the beginning of the wave. We use Japanese Ministry of Health, Labour and Welfare data on the current situation in Japan available up to 26 November 2021 corresponding to the start of the spread of Omicron. We use the average air passenger prevalence from 26 November to 31 March to approximate potential future air passenger prevalence.	Prevalence: November—1.0% December—1.6% January—6.0% February—2.2% March—1.1%	https://www.mhlw.go.jp/stf/covid-19/kokunainohasseijoukyou_00006.html
Percentage of positive cases attributed to other variants	Omicron -, Omicron +, Omicron ++, and the Vaccine escape variant are assumed to be the same as Omicron in proportion of total positive cases in air passengers towards the beginning of the wave. This is approximated in air passengers using sequencing data from Japan. Omicron assumptions: the percentage shares of Omicron cases are based on the chart 'Share of SARS-CoV-2 sequences that are the omicron variant', available on the website of the organisation 'Our World in Data', which updates COVID data daily from every country in the world.	–	Hannah Ritchie, Edouard Mathieu, Lucas Rodés-Guirao, Cameron Appel, Charlie Giattino, Esteban Ortiz-Ospina, Joe Hasell, Bobbie Macdonald, Diana Beltekian and Max Roser (2020) – 'Coronavirus Pandemic (COVID-19)'. Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/coronavirus' [Online Resource]
Omicron extrapolated starting date	As a low percentage of the population had received a booster dose while Omicron was spreading, we simulated the equivalent of what travel restrictions would have been if Omicron had started to spread in March. This extrapolation allows a more conservative approach closer to what the situation will be in the future when our simulations take place.	–	–

Assumptions on travel testing efficacy

Model input	Description	Value	Source
PCR test 72 hours before departure	We use the efficacy of pre-departure and on-arrival testing at screening incoming air passenger infectious days as a model input. We use the estimated efficacy of PCR tests 72hrs pre-departure.	45%	Oxera and Edge Health (2021), 'Assessment of the effectiveness of rapid testing for SARS-CoV-2'.
PCR test 72 hours before departure and PCR test upon arrival	We use the efficacy of pre-departure and on-arrival testing at screening incoming air passenger infectious days as a model input. We use the estimated efficacy of PCR tests 72hrs pre-departure and on-arrival PCR testing.	77%	Oxera and Edge Health (2021), 'Assessment of the effectiveness of rapid testing for SARS-CoV-2'.
No testing or quarantine	No testing or quarantine schemes are used to screen incoming air passenger infectious days.	–	Oxera and Edge Health (2021), 'Effectiveness of dual-testing schemes for air passengers'.

Assumptions on Japan booster vaccine roll-out

Model input	Description	Value	Source
Historical vaccination rates	We use daily vaccination data for Japan as published by the Nippon Hoso Kyokai (NHK) and estimate daily vaccination uptake by aggregating reported numbers of administered first, second and third doses by target groups and vaccine manufacturers.	–	https://www3.nhk.or.jp/news/special/coronavirus/data-widget/
Projected vaccination rates	We calculate the average daily vaccinations delivered in the last week of available data to estimate the speed of the vaccination roll-out in projected scenarios. We assume that the number of individuals receiving a second dose cannot exceed the number of individuals who had received a first dose three months prior. This is based on medical recommendations to get second doses within three months of the previous dose. Equally, we assume that the number of individuals receiving a third dose (booster) cannot exceed the number of individuals who have received a second dose. As the speed of vaccination roll-out is dose-specific, to prevent a violation of the assumption above in later stages of the projection, the speed of roll-out for a dose is set to the speed of the dose of the lower tier where required.	–	https://www3.nhk.or.jp/news/special/coronavirus/data-widget/

SARS-Cov-2 and variant-specific parameters (I)

Model input	Description	Value	Source
Ro	We assume that Omicron + and Omicron ++ are 1.25 and 2.5 times, respectively, more infectious than Omicron, once 7% of the population has been infected with Omicron and therefore has some form of natural immunity. The Vaccine escape variant is equally as infectious as Omicron. The Omicron - variant is 1.25 times as infectious as Omicron once 25% of the population has been infected. These factors combine in our model to result in a calculated Rt. Initial Omicron assumptions: initial data suggests that the Rt and secondary attack rates of the Omicron variant are 2 to 3 times higher than those of the Delta variant. While some of this difference is likely to be due to differing immunity for the variants in the population, we conservatively assume that Omicron is 2.5 times more infectious than Delta.	Omicron +: 9.7 Omicron ++: 19.44 Vaccine escape variant: 6.38 Omicron -: 9.44 Omicron: 8, assuming that Delta has an Ro of ~3.2 (this assumes pre-pandemic mixing patterns)	https://www.medrxiv.org/content/10.1101/2021.12.19.21268038v1.full.pdf https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1043466/20211222_OS_Daily_Omicron_Overview.pdf https://github.com/blab/rt-from-frequency-dynamics/tree/master/estimates/omicron-countries Ro of Delta: https://academic.oup.com/jtm/article/28/7/taab124/6346388
Days infectious	As reports of the duration of the infectious period for the Omicron variant are not available at the time of writing, we use the median time an individual is infectious calculated from previous variants.	7.35 days	Oxera and Edge Health (2021), 'Effectiveness of dual-testing schemes for air passengers'. For LSHTM's work see: Clifford et al. (2020), 'Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers', 25 July.
Incubation period	Preliminary evidence suggests that the time from exposure to symptoms is shorter for the Omicron variant compared to other variants.	3 days	https://www.eurosurveillance.org/content/10.2807/1560-7917.ES.2021.26.50.2101147
Impact of natural immunity (for people previously infected with the Omicron variant)	Studies conducted in England suggest that a previous history of infection reduces the risk of re-infection by 84%. Infections with previous variants were protective against infection with the Alpha variant. Immunity was observed for a minimum of seven months after initial infection. We assume that the immunity for the Omicron variant is similar, and apply scaling based on estimates of the relative efficacy of vaccines to the Omicron and Delta variants.	84% decrease in risk of infection, immune escape of 16%	https://www.sciencedirect.com/science/article/pii/S0140673621006759?casa_token=d-Aupl8roEYAAAAA:E_YnW1p75HlEH7DgPN_N_7aCANo7QcSrk93TlvcAS2khOBLt6rCwhCpwh8eYPh-bMGIscQ6k
Natural immunity for new variants compared to Omicron	Natural immunity for the Omicron -, Omicron +, Omicron ++ and the Vaccine escape variants is assumed to be the same as Omicron at the beginning. We estimate this using the relative efficacy (for vaccinated individuals with two or three doses) against Omicron compared to the Delta variant, using a weighted average of the Pfizer +Pfizer and AZ + Pfizer combination.	50%	https://www.imperial.ac.uk/media/imperial-college/medicine/mrc-gida/2021-12-16-COVID19-Report-48.pdf

SARS-Cov-2 and variant-specific parameters (II)

Model input	Description	Value	Source
Unvaccinated population who have previously been infected	We use data on confirmed cases in Japan beginning in the month of November (mainly Omicron) to project how many of the unvaccinated population will have natural immunity to Omicron by July.	7%	https://www3.nhk.or.jp/news/special/coronavirus/data-widget/
Delay between vaccination and vaccine efficacy	While immunity builds up over time after individuals are vaccinated, there is still substantial protection from vaccinations (~60%) on the first day after vaccination. Using a step function we are able to approximate this effect.	Step function, 1 week	http://www.bccdc.ca/Health-Info-Site/Documents/COVID-19_vaccine/Public_health_statement_deferred_second_dose.pdf
Estimated relative efficacy of vaccinations against new variants, based on data from Omicron	Vaccine efficacy for Omicron -, Omicron +, Omicron ++ are assumed to be the same as Omicron. The vaccine efficacy against the Vaccine escape variant is assumed to be half of Omicron. Modelling from Imperial has estimated the relative efficacy of vaccinations against Omicron, extrapolating laboratory studies to real-world efficacy. We supplement this with data on real-world efficacy, which is now starting to become available. These estimates are conservative compared to the range of scenarios estimated by other modelling groups (LSHTM). We also assume, given recent data on Omicron hospitalisation rates, that vaccines remain similarly protective against hospitalisation or death to Delta.	–	https://www.imperial.ac.uk/media/imperial-college/medicine/mrc-gida/2021-12-16-COVID19-Report-48.pdf and https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1043807/technical-briefing-33.pdf for real-world supplementary data. https://cmmid.github.io/topics/covid19/reports/omicron_england/report_11_dec_2021.pdf

Impact of local social-distancing measures on infection spread in Japan, assuming that mask requirements are lifted

Model input	Description	Value	Source
Impact of recommended masks, symptomatic and asymptomatic testing	The reduction in Rt resulting from non-pharmaceutical interventions	82.1%	https://www.medrxiv.org/content/10.1101/2020.05.28.20116129v4.full.pdf http://epidemicforecasting.org/containment-calculator https://bmcmedicine.biomedcentral.com/articles/10.1186/s12916-020-01872-8/figures/5

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