Impact of vaccination on risk of international air travel

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Contents

Figures and tables

Executive summary

In summer 2020, the UK government established travel corridors between the UK and a small number of countries that posed a low COVID-19 risk.[1] In early 2021, new policies were introduced for passengers entering the UK amid worries around variants of concern. At the same time, the UK started to roll out its vaccination programme, which has currently provided a dose of the vaccine to over 32m adults and is set to vaccinate most of the adult population by the end of July.

Currently approved vaccines, including those from Pfizer and AstraZeneca, have achieved high effectiveness in reducing severe illness. When this success is combined with higher-than-expected levels of uptake in the community, the anticipated impact on potential hospitalisations and deaths is substantial.

There are two principal benefits of the vaccination programme. The first benefit is the effect on transmission. Initial evidence suggests that the Pfizer and AstraZeneca vaccines are effective at reducing both symptomatic and asymptomatic infections. This, combined with projected uptake in adults and some pre-existing immunity from previous infections, will provide immunity to almost 60% of the population against the wild-type SARS-Cov-2[2] by the autumn.[3]

The second benefit is the impact on hospitalisation and deaths. On these critical metrics, the vaccinations perform highly, often above 95% after two doses. The targeted roll-out of the vaccine to the most vulnerable will mean that the likelihood of a vaccinated population needing hospitalisation or dying reduces to 1.2% and less than 0.1%, respectively, from early June.[4]

When both benefits are taken together, the effect of the vaccination programme is substantial. Based on the risk level established by previous travel corridors, prevalence in origin countries could be three times higher without changing domestic COVID-19 risk from air passengers. With pre-departure/on-departure testing, the threshold could increase by a factor of between six and eight.[5,6]

While we use estimates of actual prevalence in our analysis,[7] these ratios could be applied to reported incidence or prevalence in origin countries as the government develops thresholds for new travel corridors. For example, if an incidence of 20 cases per week per 100,000 people were previously accepted as a threshold for travel corridors, this threshold could be increased to 60 per 100,000 without testing and 160 per 100,000 by the end of June. By the end of

[1] Estimated prevalence in these countries was 0.03% (weighted for flight volumes). We define COVID-19 risk as secondary hospitalisation and deaths from infections passed on from air passengers.
[2] 'Wild-type' refers to the strain of virus—or background strain—that contains no major mutations.
[3] We focus on the wild type in this analysis as, at the time of writing, it is still the dominant strain globally and is therefore likely to be what most travellers from most origin countries are infected with. We treat variants (including B.1.1.7, which is now the dominant strain in the UK) in a separate analysis.
[4] Compared to an unvaccinated population of the same size.
[5] Based on estimated risk by the end of June. As social distancing is expected to still be in place by the end of May, which will therefore suppress domestic COVID-19 risk, thresholds for infection prevalence could be four times higher without tests and between seven and 11 times higher with pre-departure or on-departure testing.
[6] A corollary to this is that domestic COVID-19 risk from air passengers has decreased by a factor of 3 without testing and by a factor of 6–8 with pre-departure/on-departure testing. These scaling factors can be applied to different estimates of baseline risk levels.
[7] Accounting for underestimation in reported cases accounting for asymptomatic cases and death rates

May (as more social distancing is expected to be in place), this would be equivalent to 80 per 100,000 or 200 per 100,000.

Based on data from the summer of 2020, we have estimated that prevalence in travel corridor countries was 0.03%. The methodology used to estimate prevalence allows us to account for factors such as under-estimation of asymptomatic cases and death rates.[8] With vaccinations, the prevalence rate of 0.03% could increase to 0.2–0.3% with some form of pre-departure testing. Without any testing, the threshold would increase to 0.1%.

These new thresholds would increase the number of travel corridor countries from 62 to 102. These are illustrative of potential 'green list' countries should future travel policies take a tiered approach to risk. If there are requirements for pre-departure testing, the threshold would increase to between 122 and 131 countries. The additional 20 to 29 countries where risk is equalised with pre-departure testing are illustrative of potential 'amber list' countries should future travel policies take a tiered-risk approach.

While these estimates assume that some social distancing will remain in place for the foreseeable future, they are conservative as they assume people under the age of 18 are not vaccinated, nor do they account for vaccination programmes in other countries.

While variants of concern could still be a concern, none have yet become dominant to the wild-type SARS-Cov-2 globally.[9] Emerging variants include B.1.17 (first identified in Kent), P.1 (first identified in Brazil), and B.1.351 (first identified in South Africa).[10] Further work will examine the risk of these in more detail.

[8] Russell, T.W. et al. (2020), 'Reconstructing the early global dynamics of under-ascertained COVID-19 cases and infections', 22 September, https://doi.org/10.1101/2020.07.07.20148460
[9] Although global sequencing data is limited.
[10] Centers for Disease Control and Prevention (2021), 'Science Brief: Emerging SARS-CoV-2 Variants', 28 January, https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/scientific-brief-emerging-variants.html?CDC_AA_refVal=https%3A%2F%2Fwww.cdc.gov%2Fcoronavirus%2F2019-ncov%2Fmore%2Fscience-and-research%2Fscientific-brief-emerging-variants.html

1 Introduction

Over the last year, the UK government has introduced a number of different travel protocols to limit the risk of international air passengers importing SARS-Cov-2 infections to the UK. Travel protocols range from travel bans, to quarantine (at home or in hotels), to the requirement for multiple tests. In January 2021, travel corridors allowing individuals from certain countries to enter the UK without testing or quarantine requirements were suspended.

Vaccines are now being rolled out in the UK and in many other countries around the world. As an increasing proportion of the population in the UK and other countries are vaccinated, it is likely that the risks posed by COVID-19 will decline.

To support re-opening and recovery, one potential approach is to implement phased lifting of travel protocols for air passengers depending on the UK's domestic risk profile and departure country risk levels. This may include re-starting the travel corridor policy or a tiered-risk approach.[11] For example, as vaccines are rolled out, travel corridors could be opened to a number of green list countries without changing the transmission risk of COVID-19 from international air passengers. Adding pre-departure/on-departure test requirements for selected amber list countries would help open travel further without changing the domestic risk of COVID-19 from travel-related imported cases.

In this report, we first model the impact of the vaccination roll-out in the UK on domestic risk of infection and subsequent hospitalisation and death from COVID-19.[12] We also consider the impact of vaccinations on infection transmission rates as social-distancing measures are lifted in the UK.

We then use the results of the UK modelling as inputs for modelling the COVID-19 risk from air passengers. For different infection transmission rates and hospitalisation/death risk as vaccines are rolled out, we predict secondary infections, hospitalisations, and deaths resulting from air passengers. We benchmark the risk of secondary hospitalisations and deaths to risk levels that were accepted in the previous travel corridor policy.[13,14] We then consider how the threshold for travel corridor prevalence could change without changing secondary hospitalisation and death risk. As the speed of the vaccination roll-out varies significantly across countries, we do not explicitly model the impact of vaccination roll-out in countries other than the UK.

We also integrate earlier modelling work on the effectiveness of testing schemes[15] to consider the combined impact of testing and vaccinations on COVID-19 risk from international air passengers.

[11] Potentially through a RAG-rated travel system where green list countries do not have COVID-related travel restrictions, amber list countries have some form of pre-departure or on-departure testing, and red list countries have stricter restrictions.
[12] We focus on the wild type in this analysis as, at the time of writing, it is still the dominant strain globally and is therefore likely to be what most travellers from most origin countries are infected with. We consider variants (including B.1.1.7, which is now the dominant strain in the UK) in a separate analysis.
[13] Based on travel corridors open in July/August 2020.
[14] We note that the Joint Biosecurity Centre (JBC) has published a methodology on its risk assessments for travel corridor policy. We understand that the JBC considers a range of factors, including prevalence rates, to measure the risk from inbound passengers. However, for the purposes of our modelling, we consider the prevalence rate of incoming passengers as the key measure of risk from inbound travellers. This is because the prevalence rate is the most relevant factor in determining the impact of inbound travel on secondary cases, infections, and deaths. Furthermore, the methodology used to estimate 'actual' prevalence in this report accounts for potential under-ascertainment of cases by considering deaths and potential asymptomatic cases.
[15] Oxera and Edge Health (2021), 'Effectiveness of dual-testing schemes for air passengers', March.

The rest of the report is structured as follows:

- section 2 provides some background on how infection spread is modelled, different measures of vaccine efficacy, and the UK and international vaccination roll-out;
- section 3 sets out our methodology, focusing on vaccination roll-out projections, the impact of vaccinations on domestic COVID-19 risk, and the impact of vaccinations on COVID-19 risk from international air passengers;
- section 4 presents the results of our modelling;
- section 5 concludes.

The appendices set out further details on our assumptions and methodology, and present sensitivity analyses.

2 Background

2.1 Understanding SARS-Cov-2 infection spread

There are several factors that have made controlling SARS-Cov-2 challenging, leading to the current global pandemic.[16] In particular:

- compared to seasonal influenza, COVID-19 spreads relatively easily between individuals;
- COVID-19 has a higher hospitalisation and death risk.[17]

How easily a virus is spread from one person to another is measured by the virus's reproductive ratio (called its 'R' value). R represents the average number of secondary infections that will result from an initial infection. In epidemic modelling, there are two measures of R: R_o (the basic reproduction number or 'R nought') and R_t (the effective reproduction number).

- R_o represents the average number of secondary infections resulting from an initial infection at the beginning of an epidemic, before natural immunity starts to develop[18] and before vaccinations. It depends on the number of people susceptible to the virus at the start of a potential outbreak, the infectiousness of the virus, and how long individuals are infectious for (infectiousness ends by recovery or death). R_o does not take account of the impact of social distancing. For example, the R_o of SARS-Cov-2 is estimated to be 2.4 (this is the R_o of the most common global strain, not of emerging variants of concern).[19] This means that, on average, ten people infected in a completely susceptible population will infect 24 other people. The R_o of the B.1.17 variant of concern in the UK is estimated to be 3.2.[20] This means that, on average, ten people infected with this strain in a completely susceptible population will infect 32 other people.
- R_t, on the other hand, represents the number of secondary infections resulting from an initial case at a given point in time. It changes as more of the population becomes immune to infection (through previous infection or vaccination) and with differing levels of social distancing. Through a combination of natural immunity, social distancing, and vaccinations, the R_t value in the UK is currently estimated to be between 0.6 and 0.8.[21] This means that, on average, ten infected individuals will infect between six and eight other people.

R_o can be used to predict R_t at different levels of population immunity (through previous infection or vaccination), as social-distancing measures are lifted (i.e. back to the pre-pandemic normal).[22] For example, for a R_o of 2.4, if 40% of the

[16] Petersen et al. (2020), 'Comparing SARS-Cov-2 with SARS-Cov and influenza pandemics', 1 September, https://www.thelancet.com/journals/laninf/article/PIIS1473-3099(20)30484-9/fulltext
[17] Piroth et al. (2021), 'Comparison of the characteristics, morbidity, and mortality of COVID-19 and seasonal influenza: a nationwide, population-based retrospective cohort study', 1 March, https://www.thelancet.com/journals/lanres/article/PIIS2213-2600(20)30527-0/fulltext
[18] Natural immunity results from people getting infected and recovering from infection.
[19] Ferguson, N.M. et al. (2020), 'Report 9: Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand', 16 March, https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-NPI-modelling-16-03-2020.pdf
[20] 35% higher than that of the currently dominant strain, see King's College London (2021), 'No evidence of change in symptoms from new coronavirus variant', press release, 1 February, https://www.kcl.ac.uk/news/no-evidence-change-symptoms-new-coronavirus-variant
[21] As at 15 March 2021. See Department of Health and Social Care and SAGE (2021), 'The R value and growth rate in the UK', 19 May, https://www.gov.uk/guidance/the-r-number-in-the-uk
[22] In compartmental models of infection spread, $R_t=R_o*(1-P)$, where P is the proportion of the population immune to infection.

population were immune to SARS-Cov-2, R_t would be equal to 1.44 (2.4*(1-0.4)). If 80% of the population were immune, R_t would be equal to 0.48.

In simple models of infection spread,[23] without taking account of social distancing, infections will continue to grow exponentially until enough of the population has been infected that herd immunity is reached. Herd immunity occurs when enough people are immune to infection that the effective reproduction number (R_t) drops below one (even without social distancing). If R_t is below one, the epidemic will eventually die out.

R_o can be used to predict the extent of vaccinations or natural immunity required in a population to achieve herd immunity. Using a simple set of calculations,[24] we estimate that if R_o is 2.4, 58% of the population would have to be immune to infection to reach herd immunity. If R_o is 3.2, this increases to 69% of the population.

We do not focus on modelling UK infection spread (or on domestic herd immunity) in this analysis as travel is unlikely to have a material impact on overall domestic infection dynamics unless the R_t value is close to its tipping point (i.e. between 0.95 and 1.05).[25]

2.2 Vaccine effectiveness

Safe and effective vaccines are integral to managing the ongoing pandemic.[26] Across a population, vaccines have the combined effect of:

- preventing individuals from being infected by the virus altogether (either symptomatically or asymptomatically). This means that individuals cannot spread the virus to others;
- reducing the severity of symptoms should an individual become infected despite being vaccinated. This means that while individuals are less likely to get severely ill from COVID-19, they could still spread the virus to others.

To date, a number of studies have tested the vaccines in terms of their effectiveness at:

- preventing infection (both symptomatic and asymptomatic COVID-19 infections);
- preventing symptomatic infections of COVID-19;
- preventing severe COVID-19 or hospitalisations from COVID-19;
- preventing deaths from COVID-19.

The primary measure of vaccine effectiveness that is monitored in most clinical trials for SARS-Cov-2 vaccines is efficacy at preventing symptomatic infections. This is because it is challenging to provide trial participants with

[23] Based on compartmental models of infection dynamics – SIR and SEIR modelling. For an introduction to compartmental models of infection transmission, see Cooper, I., Mondal, A. and Antonopoulos, C.G. (2020), 'A SIR model assumption for the spread of COVID-19 in different communities', June, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7321055/. The simplest versions of these models assume homogeneous mixing in the population.
[24] In compartmental models of infection spread, $R_t=R_o*(1-P)$, where P is the proportion of the population immune to infection. Therefore, to calculate the proportion of the population that needs to be immune to infection to reach herd immunity (i.e. when Rt<1), we have re-arranged this equation to get P=1-Rt/Ro.
[25] Russel et al. (2021), 'Effect of internationally imported cases on internal spread of COVID-19: a mathematical modelling study', 1 January, https://www.thelancet.com/journals/lanpub/article/PIIS2468-2667(20)30263-2/fulltext#seccestitle10
[26] World Health Organization summary, 'COVID-19 vaccines', https://www.who.int/emergencies/diseases/novel-coronavirus-2019/covid-19-vaccines

sufficiently regular testing to monitor asymptomatic infections, and trials are usually too small to be able to assess rare outcomes such as hospitalisations and deaths.

Now that vaccines are being rolled out at pace in countries such as the UK, and in many countries around the world, more data is available on the impact of first and second doses at preventing infections, hospitalisations, and deaths. Emerging results suggest that both first and second doses are highly effective at reducing hospitalisations and deaths. Initial results based on trials of healthcare staff (who tend to be tested frequently, making it possible to detect asymptomatic infections) also suggest that vaccines are effective at reducing asymptomatic infections. In addition, very early research is emerging on the efficacy of vaccines on variants, which we cover in more detail in subsequent analysis.

To the extent that vaccines reduce both the onward risk of transmitting infections and the risk of hospitalisation/death for vaccinated individuals who do become infected, this will fundamentally change the risk of imported infections from international air travellers to the UK.

2.3 Vaccine roll-out in the UK

The UK has ordered 367m vaccine doses from seven companies—equivalent to five doses per individual.[27] At the time of writing, vaccines from three (Pfizer, AstraZeneca and Moderna) of the seven companies have been approved for use in the UK. The UK has received supplies from two companies (Pfizer and AstraZeneca) both of which are currently being used (see Table 2.1). Moderna vaccine shipments are not expected until later in the spring. For the vaccines that have already been approved, two doses are required for an individual to be fully vaccinated, although one dose still confers a high level of protection.[28]

Table 2.1 Ordered and approved doses of COVID-19 vaccines in the UK

Vaccine	Doses ordered	Development status	Vaccine technology
Pfizer/BioNTech	40m	Approved and in deployment	mRNA
Moderna	17m	Approved	
Oxford/AstraZeneca	100m	Approved and in deployment	Adenovirus
Janssen	30m	Phase 3 trials	
GlaxoSmithKline/ Sanofi Pasteur	60m	Phase 1/2 trials	Protein adjuvant
Novavax	60m	Phase 3 trials	
Valneva	60m	Phase 1/2 trials	Inactivated whole virus

Source: Department of Health and Social Care (2021), 'UK COVID-19 vaccines delivery plan', 11 January, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/951928/uk-covid-19-vaccines-delivery-plan-final.pdf.Vaccine development status current as of the 11 January 2021.

[27] For the UK government vaccine roll-out plan, see Department of Health and Social Care (2021), 'UK COVID-19 vaccines delivery plan', 11 January, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/951928/uk-covid-19-vaccines-delivery-plan-final.pdf

[28] In other words, Pfizer, Modern and AstraZeneca.

The UK government has taken a phased approach to rolling out vaccines. Vaccines are being provided to different groups based on the government's assessment of their risk of complications from COVID-19.[29] On the advice of the Joint Committee on Vaccination and Immunisation (JCVI), vaccines were first offered to health- and social-care workers and high-risk groups (care-home residents, clinically extremely vulnerable people, and the elderly), followed by moderate and low-risk groups (see Table 2.2).[30] The government met its target of offering first doses to priority groups one to four by mid-February 2021, with over 90% of the target population having received their first dose by 13 February (see Table 2.2).[31] It is now aiming to offer first doses to priority groups five to nine by mid-April 2021.

The government is planning to offer first doses to the remainder of the adult population by the end of July 2021. The Pfizer and AstraZeneca vaccines have not yet been approved for children, so the initial roll-out is for the adult population only.

[29] Residential care, healthcare, and social-care workers are being offered vaccines based on their increased risk of exposure to the SARS-Cov-2 virus and their risk of spreading it to their patients.
[30] Risk of complications from SARS-Cov-2 infections is mainly associated with age. Comorbidities are also included in the JCVI's risk stratified roll-out.
[31] Department of Health and Social Care (2021), 'UK COVID-19 vaccine uptake plan', Policy paper, 13 February, https://www.gov.uk/government/publications/covid-19-vaccination-uptake-plan/uk-covid-19-vaccine-uptake-plan

Table 2.2 JCVI cohorts and target dates for being offered first dose

Target date for first dose being offered	JCVI cohort	Priority groups	Estimated population size—UK[32]	Uptake in England as of 15 March 2021
15 February 2021	Care-home residents	1	0.3m	93.7%
	Residential care workers	1	0.5m	74.3%
	80+	2	3.3m	94.8%
	Healthcare workers	2	2.4m	94.8%
	Social care workers	2	1.4m	62.3%
	75–79	3	2.3m	100%
	70–74	4	3.2m	95.9%
	Clinically extremely vulnerable (under 70)	4	1.2m	89.5%
	Cumulative total	**1–4**	**~15m**	
15 April 2021	65–69	5	2.9m	89.2%
	At risk (under 65)	6	7.3m	
	60–64	7	1.8m	69.4%
	55–59	8	2.4m	50.0%
	50–54	9	2.8m	32.8%
	Cumulative total	**5–9**	**~17m**	
	Total	**1–9**	**~32m**	
31 July 2021	40–49	N/A	6.4m	
	30–39	N/A	6.8m	
	18–29	N/A	7.8m	
	Remainder of adult population	N/A	~21m	
	Total	**All adults in UK**	**~53m**	

Note: Adapted to separate out the remainder of the adult population into three groups: 40–49, 30–39, and 18–29 in light of recent JCVI announcements that this is how vaccines will be prioritised for the adult population (see Public Health England (2021), 'JCVI issues interim advice on Phase 2 of COVID-19 vaccination programme rollout', 26 February, https://www.gov.uk/government/news/jcvi-issues-interim-advice-on-phase-2-of-covid-19-vaccination-programme-rollout). The remainder of the adult population is split into three groups using UK 2019 demographic estimates (see ONS statistics on UK population pyramid, ONS (2020), 'Estimates of the population for the UK, England and Wales, Scotland and Northern Ireland', June, https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/populationestimatesforukenglandandwalesscotlandandnorthernireland).

Source: Department of Health and Social Care (2021), 'UK COVID-19 vaccines delivery plan', 11 January, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/951928/uk-covid-19-vaccines-delivery-plan-final.pdf.

In contrast to other countries (e.g. Israel, the USA, Canada), the UK has prioritised rolling out first doses to a greater proportion of the population rather than ensuring that each person gets the two doses within a few weeks of each other. The UK has set a target time period between first and second doses of 12 weeks. While data from AstraZeneca clinical trials suggests that a 12-week

[32] As of 10 January 2021, based on NHSEI data for England, extrapolated to the UK. Figures are approximate, as in Table 2 in Department of Health and Social Care (2021), 'UK COVID-19 vaccines delivery plan', 11 January, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/951928/uk-covid-19-vaccines-delivery-plan-final.pdf

window between first and second doses may be optimal, this was not tested in the Pfizer clinical trials (in the Pfizer trial, second doses were administered within a three- to six-week period of the first dose). Initial research from the UK suggests that the efficacy of the first Pfizer dose does not decrease even if the time period between the first and second doses is increased, although research is ongoing.

2.4 Vaccine roll-out internationally

At the time of writing, the UK has one of the highest vaccination rates in the world: it ranks fourth internationally based on the number of vaccine doses given per 100 residents, and is second based on the total number of vaccine doses given (see Table 2.3 below).

Table 2.3 Vaccine roll-out internationally

Location	Doses given per 100 residents	Total doses given
Israel	103.6	9.4m
UAE	66.9	6.5m
Maldives	38.8	206.1k
UK	38.6	25.8m
Chile	34.8	6.6m
Bahrain	33.6	0.6m
US	32.3	106.1m
Serbia	28.9	2m
Malta	23.9	120.1k
Puerto Rico	23.4	0.7m
Barbados	17.8	51k
Hungary	17.7	1.7m
Morocco	15.6	5.7m
Denmark	14.3	0.8m
Estonia	14	185.9k
Qatar	13.4	380k
Turkey	13.2	11m
Iceland	13	46.9k
Norway	12.9	0.7m
Lithuania	12.6	352.5k

Source: Figures taken from *Financial Times* (2021), 'COVID-19 vaccine tracker: the global race to vaccinate', https://ig.ft.com/coronavirus-vaccine-tracker/?areas=gbr&areas=isr&areas=usa&areas=eue&cumulative=1&populationAdjusted=0

As the speed of vaccination varies significantly across countries, we have not explicitly modelled the impact of vaccination in countries other than the UK. However, as vaccines are rolled out internationally, we expect COVID-19 risk from international travellers to decrease further.

3 Methodology

To estimate the impact of the UK's ongoing vaccination programme on domestic COVID-19 risk from inbound air passengers, we have modelled:

- the speed of the vaccination roll-out by age band, based on first and second doses already administered and government roll-out targets (section 3.1);
- decreases in infections, hospitalisations and deaths per 100,000 initial infections as vaccines are rolled out (section 3.2);
- decreases in onward transmission of the virus from international air passengers to the domestic population as vaccines are rolled out with and without testing (section 3.3).

We then calculated how high prevalence rates could be in origin countries without increasing the domestic risk of secondary hospitalisations and deaths from air passengers.

3.1 Vaccine programme

In order to estimate the number of vaccinated individuals in each age band over time we made several assumptions.

First, we estimated the number of vaccines already administered across age bands, scaling data available from NHS England to the UK.[33] We used data from 11 March 2021, which is available for the following age bands: 18–49, 50–59, 60–69, 70–79, and over 80.

We then modelled required weekly first doses to meet government commitments to offer doses to JCVI priority groups five to nine by mid-April and to all adults by the end of July (see Table 2.2). Where a group includes individuals across multiple age bands, we have used publicly available data to allocate individuals to specific age bands (outlined in Appendix A2). For example, the age distribution for JCVI priority group six (individuals under 65 and 'at risk' of severe COVID-19 due to their comorbidities) is estimated from an ONS survey on long-term conditions.[34]

To estimate required weekly second doses, we assumed that everyone is administered a second dose within 3–12 weeks after their first dose, as per government guidance.[35,36]

We then assumed that uptake of the COVID-19 vaccine will be 95% for everyone older than 50 (in JCVI groups one to nine), based on the uptake of the vaccination programme to date (see Table 2.2).[37] We conservatively assumed a 80% uptake rate for the rest of the adult population over 18 years,

[33] As age-specific vaccination data is not available at the UK level.
[34] People with long-term health conditions, UK, https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/adhocs/11478peoplewithlongtermhealthconditionsukjanuarytodecember2019
[35] We have assumed that the second dose is normally distributed with a mean of ten weeks (95% CI: 8.5–11.5 weeks).
[36] See UK government (2021), 'Chapter 14a - COVID-19 - SARS-CoV-2', 12 February, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/961287/Greenbook_chapter_14a_v7_12Feb2021.pdf
[37] Department of Health and Social Care (2021), 'UK COVID-19 vaccine uptake plan', Policy paper, 13 February, https://www.gov.uk/government/publications/covid-19-vaccination-uptake-plan/uk-covid-19-vaccine-uptake-plan

who might have more vaccine hesitancy if they perceive their COVID-19 risk to be lower.[38]

Appendix A2 includes a full list of assumptions and sources regarding the vaccine roll-out.

3.2 Impact of vaccines on domestic infection, hospitalisation, and death risk

3.2.1 Domestic infection and transmission risk

The government has published a plan on lifting domestic social distancing requirements in the coming months. Milestones from the government's COVID-19 response (spring 2021)[39] include:

- Step 1: 29 March 2021—six people or two households allowed to meet outdoors, travel outside local area allowed;
- Step 2: 12 April 2021—non-essential retail and personal care open, self-contained holiday accommodations open;
- Step 3: 17 May 2021—outdoors most social contact rules lifted, six people or two households can meet indoors;
- Step 4: 21 June 2021—all legal limits on social contact removed, hope to reopen final closed sectors of the economy.

Lifting social distancing requirements will increase infection risk in the coming months. This increase in risk will be offset by the increased immunity to infection in the population as vaccines are rolled out. To calculate how infection risk will change in the coming months, we have calculated R_t by scaling R_o (of 2.4) by:

- equivalent historical data on the impact of social distancing from the CoMix survey on contacts per individual in the UK;
- the proportion of the population immune from the virus because of vaccinations and previous infections (calculated in the simulation described in the next section).

3.2.2 Domestic hospitalisation and death risk

SARS-CoV-2 infections are concerning because of the disease—i.e. COVID-19—that they cause. While in most cases individuals have mild symptoms, or no symptoms at all, there can be severe consequences for some, such as hospitalisation and death. On average, before the vaccination programme, 5.3% of infections led to hospitalisation and 0.7% of infections led to deaths in the UK. According to the JCVI, the primary risk factor for severe COVID-19 is age. Therefore, we have focused our modelling on reductions in hospitalisation and death risk using age-stratified hospitalisation/death risk to predict decreases in overall risk in the population.[40]

[38] Based on historical uptake for other vaccination programmes. See Department of Health and Social Care (2021), 'UK COVID-19 vaccine uptake plan', Policy paper, 13 February, https://www.gov.uk/government/publications/covid-19-vaccination-uptake-plan/uk-covid-19-vaccine-uptake-plan

[39] UK government guidance, 'COVID-19 Response - Spring 2021 (Roadmap)', 22 February, https://www.gov.uk/government/publications/covid-19-response-spring-2021

[40] We have not accounted for risks associated with comorbidities, as comorbidity data for the 'at risk' groups defined by JCVI is not available for licensing outside the NHS. Furthermore, comorbidities are strongly correlated with age, so much of their impact will already be captured in our analysis.

To model the risk of infection, hospitalisation, or death from COVID-19, we simulated a sample of 100,000 infected individuals who are representative of the adult UK population. We used the infection distribution from the ONS Infection Survey[41] to assign individuals to an age bracket.[42,43] This method takes account of the relatively higher prevalence of COVID-19 in middle-age groups than younger and older age groups. Risk of hospitalisation and death have then been assigned to individuals based on published hospitalisation and death rates by age bracket. We assigned a vaccination status to individuals based on the age profiles of the priority groups defined by the JCVI and the point in time of the vaccination roll-out.

Individuals have been assigned an AstraZeneca or Pfizer vaccine in proportion to the number of doses ordered of each.[44,45] Vaccine efficacy is defined in terms of infections (symptomatic or asymptomatic), hospitalisations, or deaths, based on recent studies from the UK and Israel. Differing efficacy has been modelled depending on whether someone has been administered one or two doses. We assumed that vaccines become effective two weeks after the first dose and two weeks after the second dose has been administered—enough time for the vaccines to trigger an immune response. All of our assumptions and sources are outlined in Appendix A3.

We then combined the resultant reductions in risk from COVID-19 infection, hospitalisation, and death with modelling on imported infections from air passengers, as discussed in the following section.

3.3 Impact of vaccines on air passenger secondary infection, hospitalisation, and death risk

In June 2020 the UK instituted a travel corridor policy, whereby individuals from certain countries were permitted to enter the UK without testing or quarantine requirements.

To assess previously accepted COVID-19 risk levels from international air passengers, we first estimated prevalence in travel corridor countries in July and August 2020.[46] This estimation methodology accounts for potential underestimation of cases by accounting for underestimation of asymptomatic cases and death rates.[47] This allowed us to account for other factors, such as case positivity rate and deaths, which were considered as additional decision-making factors in the previous travel corridor policy.

We then simulated the days that infectious passengers from travel corridor countries spent in the UK community in July and August 2020 (our

[41] Coronavirus (COVID-19) ONS Infection Survey, see: https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/datasets/coronaviruscovid19infectionsurveydata
[42] To calculate the percentage of the population immune to COVID-19 because of their vaccination (results presented in section 4.2.1), we have applied this simulation methodology to the UK population pyramid.
[43] We have focused on adults as the vaccination programme is currently not targeting children and it is extremely rare for children under the age of 18 to be hospitalised or to die from COVID-19. See UK government (2021), 'Chapter 14a - COVID-19 - SARS-CoV-2', 12 February, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/961287/Greenbook_chapter_14a_v7_12Feb2021.pdf
[44] Moderna vaccines have been approved and ordered but supplies are not expected until the spring. Therefore, we have only considered the AstraZeneca and Pfizer vaccines.
[45] Based on reports from Public Health England on one-dose efficacy and reports from Israel on two-dose Pfizer efficacy, we have assumed that the protection against hospitalisation and death are the same across both brands of vaccine. As more data is released on two-dose AstraZeneca hospitalisation and death efficacy, the model can be adapted to incorporate it.
[46] Russell, T.W. et al. (2020), 'Reconstructing the early global dynamics of under-ascertained COVID-19 cases and infections', 22 September, https://doi.org/10.1101/2020.07.07.20148460
[47] For example, scenarios where there are a high number of deaths and low cases could be indicative of cases being under-estimated.

methodology and assumptions are outlined in Appendix A3). We assumed no testing and/or quarantine measures for the arriving passengers. We used the measure of infectious days as it allowed us to account for the time that air passengers spend in their origin country (rather than the UK) while infectious and to account for differing infection risk from symptomatic and asymptomatic passengers.

We then used government estimates[48] of R_t values in the UK in July/August 2020[49] to derive the number of secondary infections in the community that resulted from air passengers (see Appendix A3.2 for our calculation methodology). Using the estimated risk of hospitalisation or death following infection before the vaccination roll-out,[50] we calculated the number of secondary hospitalisations and deaths that might have resulted from passengers coming from travel corridor countries.

We used this as a baseline for acceptable risk for establishing new travel corridors as hospitalisation/death risk decreases in the coming months as vaccinations are rolled. As outlined in section 3.2, the risk of infection, hospitalisation, and death decreases following immunisation. This affects risk from air passengers in two ways:

- by decreasing domestic Rt, in turn decreasing the number of secondary infections resulting from a single base case;
- by decreasing the risk of hospitalisation or death, should an individual become infected.

Therefore, as vaccines are rolled out, passengers from higher prevalence countries will now present the same or lower overall risk to the UK population.

[48] For more on R value and its growth rate in the UK, see Department of Health and Social Care and SAGE (2021), 'The R value and growth rate in the UK', 19 May, https://www.gov.uk/guidance/the-r-number-in-the-uk

[49] We used July/August 2020 as it was a period of relatively low global infection levels, thus creating a stringent benchmark.

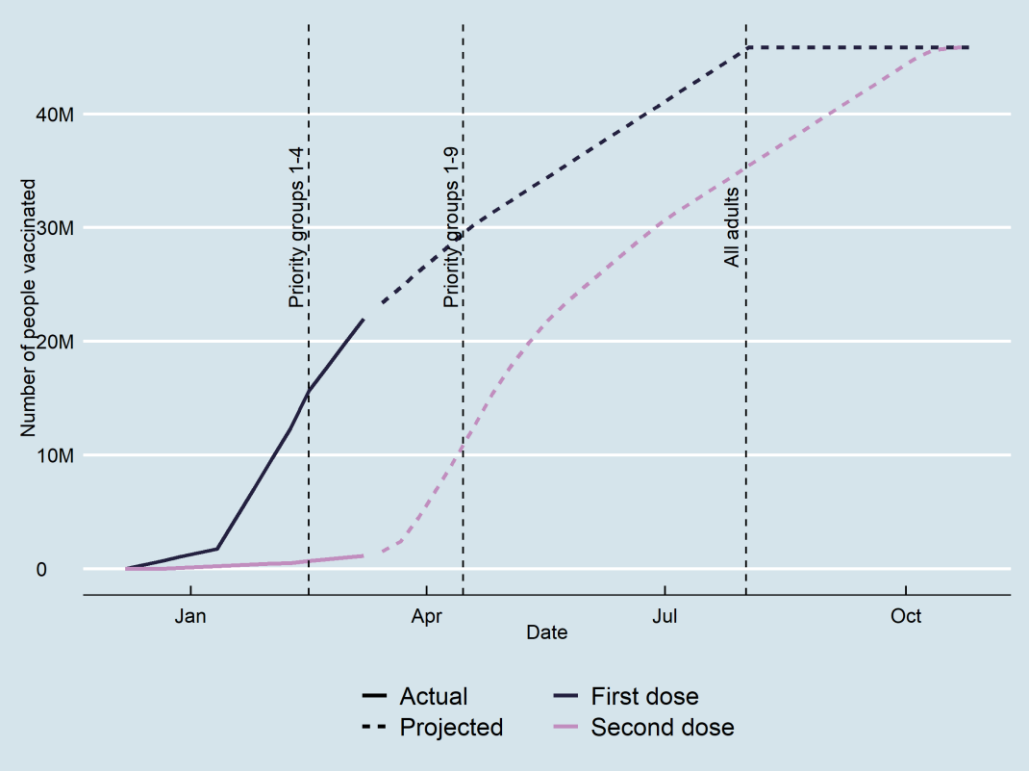
[50] Based on weighing the infection prevalence per age group by estimated hospitalisation and death conversion rates for England. Hospitalisation and death risk from infection based on modelling from antibody data. See Table S 9 of Imperial College COVID-19 response team (2020), 'SUPPLEMENTARY MATERIALS - Report 41: The 2020 SARS-CoV-2 epidemic in England: key epidemiological drivers and impact of Interventions', 22 December, https://www.imperial.ac.uk/media/imperial-college/medicine/mrc-gida/2020-12-22-COVID19-Report-41-supplement.pdf

4 Results

4.1 Vaccine roll-out

Based on vaccinations administered to date, government targets, and our assumptions around vaccine uptake,[51] the UK is projected to administer 91.6m first and second doses of vaccines to 45.8m people by the end of October 2021 (see Figure 4.1). This amounts to an average of 2.1m vaccines per week. Currently 2.5m vaccines are being administered per week, suggesting that capacity is on track to meet this target.[52]

Figure 4.1 Number of people vaccinated in the UK, for first and second doses

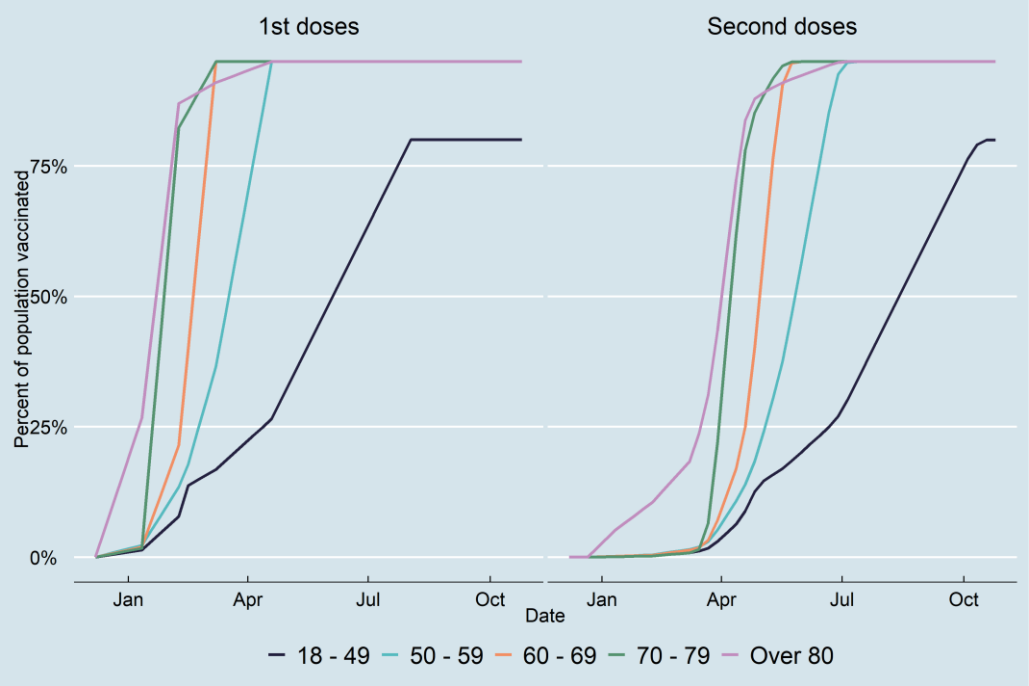


Source: Oxera and Edge Health.

We have assumed that 95% of the population over 50 will have received their first dose by mid-April and that 95% of the population over 50 will have received their second dose by the end of July. We have assumed that 80% of individuals between 18 and 49 will have received their first dose by the end of July and that 80% will have received their second dose by the end of October. Figure 4.2 illustrates our modelled uptake rates over time.

[51] Vaccine uptake rates of 95% in JVCI priority groups 1–9 over 50 and 80% in healthy adults.
[52] Based on an average of first and second doses administered in the weeks between 21 February and 7 March 2021.

Figure 4.2 Percentage of the population vaccinated by age group and dose



Source: Oxera and Edge Health.

4.2 Impact of vaccines on domestic COVID-19 risk

4.2.1 Impact of vaccines on infection risk

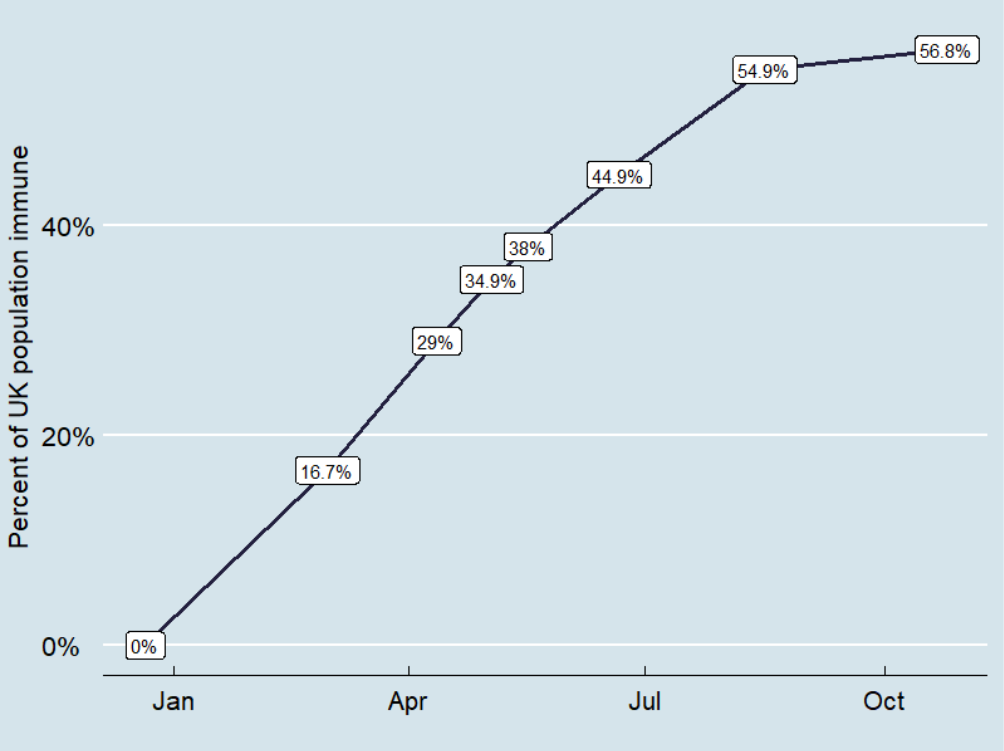
As vaccines are rolled out, they will reduce infections by making individuals in the UK population immune to infection from SARS-Cov-2. Being immune to infection means that when an individual is exposed to the virus they will not become infected and thus cannot transmit the virus to others. For a simulated population of 100,000 individuals in the UK,[53] we have modelled how immunity from vaccines will increase over time (see Figure 4.3 below).

The extent of immunity from vaccines in the population depends both on the extent of the vaccine roll-out and on the efficacy of vaccines at preventing infections. As vaccines are not 100% effective at reducing infections, immunity from vaccinations is lower than the percentage of the population vaccinated.

Infection immunity continues to increase until mid-August before plateauing at 55% (see Figure 4.3 below). At this point, we have assumed that 86% of adults (representing 70% of the overall population when children under 18 are included) will have received at least one vaccine dose.[54] We have also assumed that 70% of adults will have received their second dose by mid-August (equivalent to 56% of the population when children are included). The proportion of the population who will be immune increases slightly by the end of October, as an additional 10% of the adult population receives their second dose.

[53] Based on the UK population pyramid.
[54] As children under 18 have a slightly lower infection prevalence relative to their population size, this amounts to 72% of the infected population.

Figure 4.3 Estimated percentage of the UK population immune to infection from vaccinations



Source: Oxera and Edge Health.

In addition to immunity from vaccines, recent studies on antibody prevalence in the population indicate that 10% of the unvaccinated population have antibodies.[55] Assuming that these individuals are immune to infection, this would mean that an additional 5% of the population would still have natural immunity by mid-August.

This data on immunity from vaccinations and on natural immunity has allowed us to estimate what R_t (the number of secondary infections from an initial infection) would be without social distancing (column 2 in Table 4.1 below). We have calculated R_t based on a R_o value of 2.4—the R_o value of the most common global variant.

However, in the UK there are still some social-distancing requirements in place, which will be lifted gradually in the coming months. It is currently planned that most mandatory social-distancing requirements will be lifted by 21 June 2021 (with the exception of masks). Therefore, we have also modelled R_t scaled by historical social-distancing trends (column 4 in Table 4.1).[56]

[55] Based on England estimates, see: Ward et al. (2021), 'REACT-2 Round 5: increasing prevalence of SARS-CoV-2 antibodies demonstrate impact of the second wave and of vaccine roll-out in England', 1 March, https://www.medrxiv.org/content/10.1101/2021.02.26.21252512v1.full.pdf
[56] Based on the LSHTM CoMix surveys. For all historical CoMix reports, see Centre for Mathematical Modelling of Infectious Diseases, 'CoMix study - Social contact survey in the UK', https://cmmid.github.io/topics/covid19/comix-reports.html

Table 4.1 Predicted R_t values with and without social distancing

Date	R_t value (without social distancing)	Social-distancing scaling factor	R_t value (with social distancing)
7 Dec 2020	2.2	--[57]	1.2
1 Mar 2021	1.8	-- [58]	0.7
17 May 2021	1.4	0.4	0.6
21 Jun 2021	1.2	0.6	0.7
16 Aug 2021	1.0	0.8	0.8

Source: Oxera and Edge Health.

These estimates are conservative, as preliminary evidence from studies conducted by AstraZeneca suggests that even when individuals test positive following vaccination, they may be less infectious than unvaccinated positive cases. The viral loads of positive vaccinated cases tend to be lower and shed the virus for less time than for positive cases in unvaccinated individuals.[59,60]

Our estimates are also conservative because we have assumed that individuals under the age of 18 have an equal role in spreading the virus as other age groups (based on recorded prevalence in this age group from the ONS Infection Survey). However, children are highly likely to be asymptomatic and typically only exhibit mild symptoms.[61] Therefore, they may have a relatively limited role in spreading the virus (although evidence on this is mixed).[62]

4.2.2 Impact of vaccines on hospitalisation and death risk

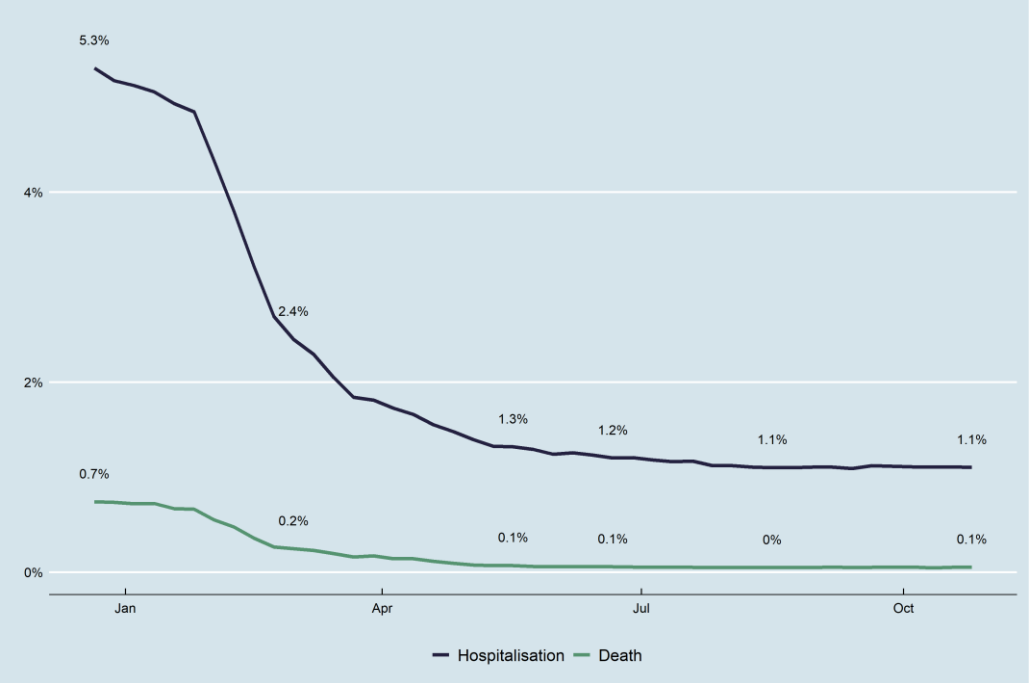
In addition to reducing hospitalisations and deaths by preventing infections, vaccines decrease the risk of hospitalisation and death even if vaccinated individuals become infected. Therefore, hospitalisations and deaths are projected to drop even more sharply than infections as vaccinations are rolled out.

For a simulated population of 100,000 initial infections in the UK,[63,64] we have modelled how hospitalisation and death risk would decrease as vaccinations are rolled out (see Figure 4.4 below). Before vaccinations, the risk of being hospitalised or dying following an infection was estimated to be 5.3% and 0.7%, respectively, for the UK population. As vaccinations are rolled out, the risk of hospitalisation or death decreases to 1.1% and 0.1%, respectively.

[57] We have used the currently reported R_t value for the UK in December here; therefore, we do not require a social-distancing scaling factor.
[58] We have used the currently reported R_t value for the UK in March here; therefore, we do not require a social-distancing scaling factor. This is a conservative assumption as the B.1.17 variant is now dominant in the UK—R_t for the wildtype may be even lower.
[59] Voysey et al., (2021), 'Single Dose Administration, And The Influence Of The Timing Of The Booster Dose On Immunogenicity and Efficacy Of ChAdOx1 nCoV-19 (AZD1222) Vaccine', 1 February, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3777268
[60] Studies on transmission from positive cases where individuals have been vaccinated could help determine the extent to which vaccination reduces transmission even when an individual eventually tests positive.
[61] Flasche, S. and Edmunds, W.J. (2020), 'The role of schools and school-aged children in SARS-CoV-2 transmission', 8 December, https://www.thelancet.com/journals/laninf/article/PIIS1473-3099(20)30927-0/fulltext
[62] Ibid.
[63] Based on age-stratified infection prevalence reported by the ONS Infection Survey for England.
[64] We began by simulating 100,000 infections pre-vaccination. As vaccines are rolled out, infections will begin to drop, along with hospitalisations and deaths.

Figure 4.4 shows that hospitalisation and death risk decreases until April, at which point it starts to plateau. This is because the hospitalisation and death risk for the remaining unvaccinated population (adults 18–49 and children) is already extremely low. In line with JCVI vaccination roll-out priorities, vaccinating older and higher-risk groups has the largest impact on overall hospitalisation and mortality risk from SARS-Cov-2 infections.

Figure 4.4 Risk of hospitalisation or death in a vaccinated population compared to an unvaccinated population, based on a simulation of the UK



Source: Oxera and Edge Health.

4.3 Impact of vaccines on air passenger transmission risk

There are already a number of protocols in place (such as testing) to ensure that infected air passengers do not enter the UK. As vaccines are rolled out, the risk to the domestic population from infected international air passengers will continue to decrease, provided that lifting social-distancing restrictions does not increase R_t substantially.

We have benchmarked changes to domestic COVID-19 risk from air passengers as vaccines are rolled out and social distancing is lifted to the domestic COVID-19 risk from air passengers from travel corridors over July/August 2020. We have assumed that air passengers from travel corridors enter the community directly, without any quarantine or testing requirements. The average infection prevalence in travel corridor countries was low in July/August 2020—the weighted prevalence across countries was 0.033%.[65] Based on our simulation modelling infection risk from air passengers (our methodology is outlined in detail in Appendix A4), this would have resulted in 983 infectious days imported to the UK per 1m passengers. Based on the average R_t in July/August 2020 (0.86), these infectious days would have resulted in 115 secondary infections. Based on pre-vaccination hospitalisation

[65] Weighting based on incoming flight volumes.

and death risk levels, this would have resulted in 6.1 secondary hospitalisations and 0.87 secondary deaths (see Table 4.2).

Table 4.2 July/August 2020 domestic infection risk from travel corridors

Date	Prevalence	Infectious days spent in the community per 1m arrivals	R_t value	Secondary infections per 1m arrivals	Hospitalisations per 1m arrivals	Deaths per 1m arrivals
Jul/Aug 2020	0.033%	983	0.864	115	6.1	0.87

Source: Oxera and Edge Health.

As vaccinations increase in the coming months and UK social-distancing measures are lifted, we expect R_t to change. Vaccinations increasing immunity in the population will reduce R_t, while lifting social-distancing measures will increase R_t. Provided that increased immunity from vaccinations (combined with decreasing hospitalisation and death risk) compensates for lifting social-distancing measures, the number of secondary infections, hospitalisations and deaths resulting from imported cases from air passengers will decrease. A corollary to this is that the prevalence rates in travel corridor countries could increase without changing the relative risk of secondary hospitalisations or deaths. This means that, should travel corridors re-open, they could be opened for a larger group of countries.

We have modelled prevalence levels that would lead to the same relative risk of hospitalisation or death (6.1 and 0.87 per million passengers, respectively) as the July/August 2020 travel corridors. For this, we have used the predicted R_t values (scaled for social distancing) calculated in Table 4.1 and the predicted hospitalisation and death conversion rates from Figure 4.4.[66] We have modelled prevalence levels that would lead to the same relative risk of hospitalisation or death under three scenarios:

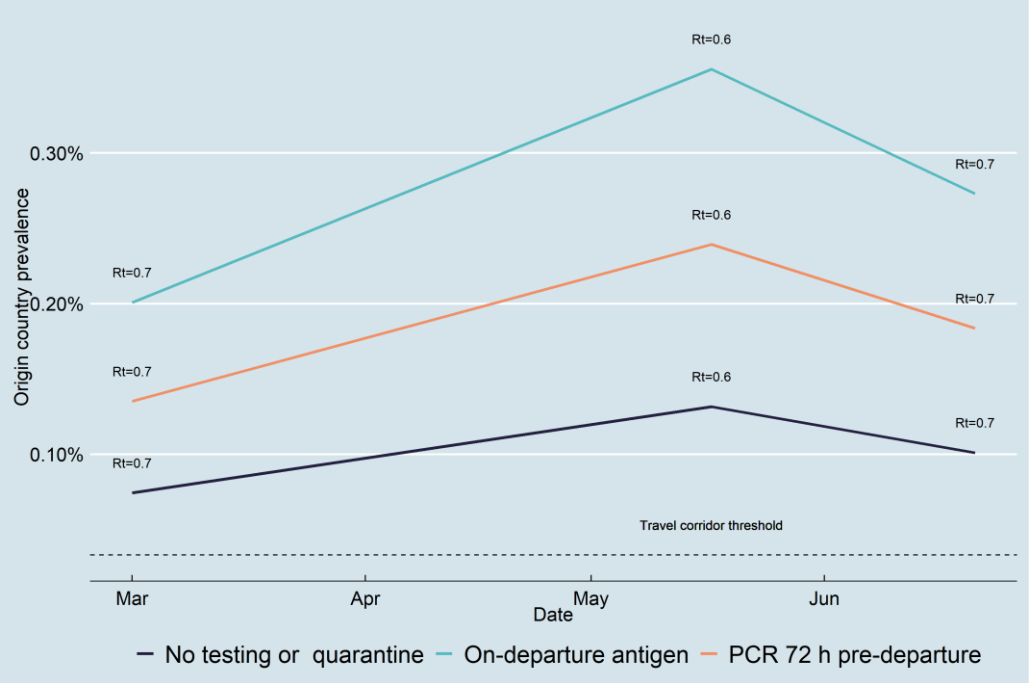
- without any testing or quarantine requirements;
- with a PCR test 72 hours pre-departure—in previous modelling we found that a PCR test 72 hours pre-departure would screen 45% of infectious days;
- with an antigen test administered on departure—in previous modelling an antigen test on departure screens 62% of infectious days.[67]

Figure 4.5 below presents the results of this modelling. The combination of increased vaccinations with decreased social distancing means that R_t may be lower in mid-May compared to the end of June when most social-distancing measures are set to be removed. This is why the estimated origin country prevalence equivalent to the hospitalisation or death risk from travel corridor countries is slightly higher in May than in June.

[66] Conversion rates from Figure 4.4 are scaled by the number of infections to calculate the conditional probability of hospitalisation or death given an infection.
[67] Oxera and Edge Health (2021). 'Analysis of the effectiveness of rapid tests for SARS-CoV-2', 25 March. Antigen testing is projected to screen additional infectious days as the test is administered closer to the time of departure.

Overall, this shows that if travel corridors were to be re-established in the coming months, the allowed prevalence could be three times higher than it was previously without changing COVID-19 hospitalisation or death risk. If pre-departure PCR tests or an on-departure antigen test were to be used as well, origin country prevalence could be six (PCR testing) to eight (antigen testing) times higher without changing COVID-19 hospitalisation or death risk.

Figure 4.5 Origin country prevalence equivalent to travel corridor COVID-19 hospitalisation and death risk per 1m passengers



Source: Oxera and Edge Health.

The increased travel corridor prevalence threshold by 17 May 2021 and 21 June 2021 would mean that more countries with higher prevalence could be added to the corridor list without changing the domestic risk from COVID-19. Furthermore, as approximately 60% of international arrivals to the UK are UK residents, we would expect that some of these passengers would be immune to infection while abroad (based on current projections of the UK vaccination programme, see section 4.2.1).[68] Therefore, the prevalence of inbound air passengers to the UK is expected to be lower than that of the origin country.

Assuming that origin countries have similar estimated prevalence as they did in July/August 2020,[69] the combined impact of increased travel corridor prevalence thresholds and increased immunity in UK air passengers would result in a high proportion of origin countries potentially qualifying as green and amber list countries, should the government opt to adopt a tiered-risk approach to future travel policy (see Appendix A5 for a full list of countries where estimated prevalence was available). 43% (62 out of 143) countries qualified at the previous travel corridor threshold. When the impact of vaccines is taken into account, the UK could create travel corridors with 71% of the countries without changing COVID-19 risk (per million passengers) to the UK. As

[68] See Table 2 of Civil Aviation Authority, '2019 Passenger survey report', https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Consumer-research/Departing-passenger-survey/2019-Passenger-survey-report/

[69] We have made this assumption as global prevalence (in the Northern Hemisphere) is expected to be lower during the spring/summer months (i.e. 17 May 2021 and 21 June 2021), with more people likely to socially distance outdoors, making social distancing easier.

illustrated in Table 4.3, when pre-departure/on-departure testing is added, the UK could open travel to 92% of countries without changing COVID-19 risk (per million passengers) to the UK.

Table 4.3 Travel corridors when accounting for the impact of vaccines

Travel re-open date	Prevalence threshold	Testing scheme	Countries with risk equalised	EU countries with risk equalised[70]
17 May 2021	0.13%	No testing or quarantine	106 of 143 or 74%	24 of 26 or 92%
	0.24%	PCR 72 h pre-departure	127 of 143 or 89%	25 of 26 or 96%
	0.35%	Antigen on departure	134 of 143 or 94%	26 of 26 or 100%
21 June 2021	0.10%	No testing or quarantine	102 out of 143 or 71%	24 of 26 or 92%
	0.18%	PCR 72 h pre-departure	122 out of 143 or 85%	25 of 26 or 96%
	0.27%	Antigen on departure	131 out of 143 or 92%	26 of 26 or 100%

Source: Oxera and Edge Health.

In Appendix A6, we present a sensitivity analysis, where we have assumed that prevalence in origin countries remains at current levels (as of 14 March 2021) rather than using prevalence levels from July/August 2020. In Appendix A7, we illustrate how domestic COVID-19 risk from air passengers decreases with the UK vaccination roll-out for three example markets (Spain, Turkey, the USA).

[70] Estimated prevalence data for Malta was unavailable.

5 Conclusion

Vaccines reduce the risk of imported infections, both by reducing secondary infections from travellers and by decreasing the severity of COVID-19, resulting in fewer hospitalisations and deaths.

Overall, this means that prevalence in origin countries could be three times higher than previous travel corridors without changing domestic COVID-19 risk from air passengers. With pre-departure/on-departure testing, prevalence could increase by a factor of between 6 and 8.[71,72]

While we use estimates of actual prevalence in our analysis,[73] these ratios could be applied to reported incidence or prevalence in origin countries as the government develops thresholds for new travel corridors. For example, if an incidence of 20 cases per week per 100,000 people was previously accepted as a threshold for travel corridors, this threshold could be increased to 60 per 100,000 without testing and 160 per 100,000 by the end of June. By the end of May (as more social distancing is expected to be in place), this would be equivalent to 80 per 100,000 or 200 per 100,000.

Over July/August 2020, travel corridors were a relatively effective mechanism of reducing the risk of SARS-Cov-2 infections entering the UK. These corridors set an acceptable level of risk where passengers from certain countries were not required to undergo testing or quarantine. If travel corridors are reinstated with similar thresholds and May/June vaccination levels, corridors would be likely to apply to 70% of origin countries (102 out of 143 countries where estimates of prevalence are available), compared to 43% of countries in July/August 2020. These are illustrative of potential green list countries should future travel policies take a tiered-risk approach. As vaccinations are rolled out globally, infection prevalence may decrease compared to July/August in origin countries. This means that these may be conservative estimates of the number of countries that would qualify for green listing should they be reinstated at similar risk thresholds.

Furthermore, if pre-departure PCR or on-departure antigen testing were applied to certain origin countries, this would mean that travel corridors could be created with between 85% (122 of 143) and 92% (131 of 143) of origin countries without changing the relative domestic COVID-19 risk from air passengers. The additional 20–29 countries where risk is equalised with pre-departure or on-departure testing are illustrative of potential amber list countries should future travel policies take a tiered-risk approach.

This suggests that, variants of concern notwithstanding, a combination of travel corridors without testing or quarantine requirements and pre-departure testing should allow travel to be opened from the vast majority of countries. Further work will examine the impact of variants of concern on these results.

[71] Based on estimated risk by the end of June. As social distancing is expected to still be in place by the end of May, which will therefore suppress domestic COVID-19 risk, thresholds for infection prevalence could be four times higher without tests and between seven and 11 times higher with pre-departure or on-departure testing.
[72] This is equivalent to saying that domestic COVID-19 risk from air passengers has decreased by three times without considering any testing regime, and by six to eight times with pre-departure/on-departure testing.
[73] Accounting for underestimation in reported cases accounting for asymptomatic cases and death rates

A1 Vaccine roll-out assumptions and sources

Model input	Description	Value	Source
	Actual vaccine roll-out to data		
UK-wide first and second doses administered	At the UK-level, PHE publishes daily 1st and 2nd vaccine doses administered.	See data source	https://coronavirus.data.gov.uk/details/vaccinations
England first and second doses by age band	At the England level, NHSEI publishes 1st and 2nd vaccine doses administered by age band. As doses by age band are not available at the UK-level, these England-level proportions are applied to all four nations.	See data source	https://www.england.nhs.uk/statistics/statistical-work-areas/covid-19-vaccinations/
	Modelled vaccine roll-out		
Priority groups for vaccination	The UK government has published which groups they will prioritise for vaccinations, along with their approximate population sizes. These targets are used to assess how many vaccinations should be delivered by key dates.	See data source	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/951928/uk-covid-19 - vaccines-delivery-plan-final.pdf
Age distribution of care home residents	The UK government identified priority group number 1 as those living in care homes. We estimate their age distribution using publicly available data from census data.	See data source	https://www.nomisweb.co.uk/census/2011/ST126/view/2092957699?rows=commtype&cols=c_age
Age distribution of care home workers	The UK government identified priority group number 1 as those working in care homes. We estimate their age distribution using publicly available data from NHS Employers.	See data source	https://www.nhsemployers.org/case-studies-and-resources/2019/05/age-in-the-nhs-infographic
Age distribution of healthcare workers	The UK government identified priority group number 2 as those working in healthcare. We estimate their age distribution using publicly available data from NHS Employers.	See data source	https://www.nhsemployers.org/case-studies-and-resources/2019/05/age-in-the-nhs-infographic
Age distribution of social care workers	The UK government identified priority group number 2 as those working in social care. We estimate their age distribution using publicly available data from NHS Employers.	See data source	https://www.nhsemployers.org/case-studies-and-resources/2019/05/age-in-the-nhs-infographic
Age distribution of clinically extremely vulnerable under age 70	The UK government identified priority group number 4 as those clinically extremely vulnerable under the age of 70. To estimate this group's age distribution, we use NHS Digital data on the shielded population. The Shielded Patient List (SPL) is a record of vulnerable patients thought to be at high risk of complications from COVID-19.	See data source	https://digital.nhs.uk/coronavirus/shielded-patient-list
Age distribution of those clinically at risk (Under 65)	The UK government identified priority group number 6 as those who are clinically at risk and under the age of 65. To estimate this group's age distribution, we use ONS survey data of those with long-term conditions (information on the clinical codes the government is using to identify this cohort is only available for licensing for NHS organisations).	See data source	https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/adhocs/11478peoplewithlongtermhealthconditionsukjanuarytodecember2019

Model input	Description	Value	Source
Vaccine roll-out targets - first doses	The UK government has published indicative dates where they are aiming to have the first vaccinations for each of their defined cohorts delivered.	Feb 15th - 1st doses to JCVI groups 1-4;	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/951928/uk-covid-19-vaccines-delivery-plan-final.pdf
Delay between first and second doses	The UK government has recommended that second doses be administered between 3-12 weeks after the first dose. To estimate the timing of people receiving their second dose from first dose targets, we assume a normal distribution centred at 10 weeks.	Normal distribution centred at 10 weeks with a standard deviation of .75 weeks	https://www.nhs.uk/conditions/coronavirus-covid-19/coronavirus-vaccination/coronavirus-vaccine/
Vaccine uptake	Vaccine uptake in the highest-risk groups has been high so far.	95% in JCVI priority groups 1-9 50+; 80% in the rest of the adult population.	Based on calculations of vaccine uptake in priority groups age 60+ to date.

A2 Domestic COVID-19 risk assumptions and sources

Model input	Description	Value	Source
Distribution of infections by age band	We assume that age-stratified prevalence is equivalent to that reported in the ONS Infection Survey. We use age-stratified infection prevalence from England.	Table 1d in excel download	https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/datasets/coronaviruscovid19infectionsurveydata
Infection to hospitalisation conversion rate	Age-stratified infection hospitalisation risk in England, scaled to the population pyramid of the UK.	(Table S 9)	https://www.imperial.ac.uk/media/imperial-college/medicine/mrc-gida/2020-12-22-COVID19-Report-41-supplement.pdf
Infection to death conversion rate	Age-stratified infection death risk in England, scaled to the population pyramid of the UK.	(Table S 9)	https://www.imperial.ac.uk/media/imperial-college/medicine/mrc-gida/2020-12-22-COVID19-Report-41-supplement.pdf
Vaccine brand administered	The type of vaccine administered in the simulation model is based on the relative proportion of Pfizer and AstraZeneca vaccines administered.	Pfizer - 40 m doses (29%); AstraZeneca - 100 m doses (71%)	https://www.gov.uk/government/news/jcvi-issues-interim-advice-on-phase-2-of-covid-19-vaccination-programme-rollout
1 dose of Pfizer/AstraZeneca, efficacy at preventing hospitalisation	Efficacy at preventing hospitalisation of aggregated Pfizer or AstraZeneca vaccine data, based on an analysis of vaccines administered to those 80+ by Public Health England. Results based on data available for those 80+.	80%	https://khub.net/documents/135939561/430986542/Early%20effectiveness%20of%20COVID%20vaccines.pdf/ffd7161c-b255-8e88-c2dc-88979fc2cc1b?t=1614617945615
1 dose of Pfizer/AstraZeneca, efficacy at preventing death	Efficacy at preventing death of aggregated Pfizer or AstraZeneca vaccine data, based on an analysis of vaccines administered to those 80+ by Public Health England. Results based on data available for those 80+.	85%	https://khub.net/documents/135939561/430986542/Early%20effectiveness%20of%20COVID%20vaccines.pdf/ffd7161c-b255-8e88-c2dc-88979fc2cc1b?t=1614617945615
1 dose of Pfizer, efficacy at preventing asymptomatic and symptomatic infections	Efficacy at preventing all infections (both symptomatic and asymptomatic), based on a prospective cohort study of healthcare workers in England.	72%	https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3790399
1 dose of AstraZeneca, efficacy at preventing asymptomatic and symptomatic infections	Efficacy at preventing all infections (both symptomatic and asymptomatic), based on an analysis of Phase III trial data.	67%	https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3777268

Model input	Description	Value	Source
2 doses of Pfizer, efficacy at preventing hospitalisation. Assumed to be the same for AstraZeneca.	Pfizer's efficacy at preventing hospitalisations after 2 doses, based on analysis of data from Israel. Data from Israel is used as they were the earliest country to administer a significant number of second doses. Assumed to be the same for AstraZeneca as sufficient data on the impact of the second dose is not yet available. In phase III AstraZeneca clinical trials, no one in the vaccinated group was hospitalised (100% efficacy, but only based on a small sample size).	87%	https://www.nejm.org/doi/10.1056/NEJMoa2101765 https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3777268
2 doses of Pfizer, efficacy at preventing death. Assumed to be the same for AstraZeneca.	Pfizer's efficacy at preventing deaths after 2 doses of the vaccine, based on Israel Ministry of Health and Pfizer/BioNTech analysis. Data from Israel is used as they were the earliest country to administer a significant number of second doses. Assumed to be the same for AstraZeneca as sufficient data on the impact of the second dose is not yet available. In phase III AstraZeneca clinical trials, no one in the vaccinated group died (100% efficacy, but based on a small sample size).	97%	https://www.pfizer.com/news/press-release/press-release-detail/real-world-evidence-confirms-high-effectiveness-pfizer https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3777268
2 doses of AstraZeneca, efficacy at preventing asymptomatic and symptomatic infections	Efficacy at preventing all infections (both symptomatic and asymptomatic), based on results for the wildtype.	80%	https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3779160
2 doses of Pfizer, efficacy at preventing asymptomatic and symptomatic infections	Efficacy at preventing all infections (both symptomatic and asymptomatic), based on a prospective cohort study of healthcare workers in England.	86%	https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3790399
Delay to 1st dose efficacy	We assume that the first dose of either vaccine becomes effective 14 days post-vaccination.	14 days	Assumption
Delay to 2nd dose efficacy	We assume that the second dose of either vaccine becomes effective 14 days post-vaccination.	14 days	Assumption

A3 Air traveller transmission risk assumptions and calculations

A3.1 Assumptions and sources

Model input	Description	Value	Source
Infectious days entering the community	We calculate infectious days potentially entering the community from travel corridors based on previous modelling work (see Appendix A5 for full description of assumptions and modelling inputs). We modelled the do-nothing scenario without testing or quarantine requirements and with PCR D-72 and D=0.	-	See Oxera and Edge Health (2021),Assessment of the effectiveness of rapid testing for SARS-Cov-2'. For 'LSHTM work see: Clifford et al. (2020), 'Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers', 25 July.
Median duration infectious	We estimate the median number of infectious days per individuals without testing or quarantine schemes.	7.35	See Oxera and Edge Health (2021), 'Assessment of the effectiveness of rapid testing for SARS-Cov-2'. For LSHTM work see: Clifford et al. (2020), 'Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers', 25 July.
Domestic Rt-value, summer 2020	We use the average Rt value over the summer of 2020 in modelling to estimate the number of secondary infections from air passengers.	0.86	https://www.gov.uk/guidance/the-r-number-in-the-uk#:~:text=The%20R%20number%20range%20for,as%20of%2021%20August%202020.&text=The%20R%20number%20range%20for,as%20of%2014%20August%202020
Ro for COVID-19	Ro is the baseline number of secondary infections from a base-case, assuming a completely susceptible population and no social distancing measures. As the variant B.1.17 now represents most new UK cases, we use it's Ro value.	3.2	https://www.medrxiv.org/content/10.1101/2020.12.27.20248896v2.full.pdf

A3.2 Calculations

We have estimated secondary infections, hospitalisations, and deaths resulting from infectious days that air passengers potentially spend in the community as follows:

$$1)\ (Infectious\ days)_{Travellers} \times R_t \div (Days\ infectious)_{Population} = Secondary\ infections$$

$$2)\ Secondary\ infections * (Age\ weighed\ hospitalisation\ rate) = Secondary\ hospitalisations$$

$$3)\ Secondary\ infections * (Age\ weighed\ hospitalisation\ rate) = Secondary\ deaths$$

A4 Summary of infectious days modelling

We used Monte Carlo methods to simulate infectious days potentially entering the UK from air passengers. We evaluated this for three scenarios: without testing (assuming that the only reason a passenger opts not to fly is due to symptoms pre-departure); with a PCR test 72 hours pre-departure; and with an antigen test on departure. Our focus was on passengers arriving in the UK from travel corridor countries in summer 2020.

A4.1 Summary of modelling approach

As previously summarised in Oxera and Edge Health (2021), 'Assessment of the effectiveness of rapid testing for SARS-Cov-2' and Oxera and Edge Health (2021), 'Effectiveness of dual-testing schemes for air passengers', we simulated:

- the proportion of passengers intending to travel who are expected to be infected, based on infection prevalence in the departure country;[74]
- the proportion of infected passengers who develop symptoms or who are infected but asymptomatic;
- how infections evolve for each infected passenger. For symptomatic individuals this includes: time from initial infection to symptom onset, duration of symptoms, as well as time from initial infection to infectiousness and infectiousness duration. For asymptomatic individuals this includes: time from initial infection to infectiousness and infectiousness duration.
- the time from initial infection to flight departure;
- compliance with quarantine for three scenarios: i) if an individual becomes symptomatic in their departure country or once they have arrived in their destination country; ii) government requirements to quarantine post-arrival while waiting to be tested; iii) if an individual receives a positive test result.

These parameters are combined to create a number of potential passenger journeys. For example, some of the simulated passengers may become infected but no longer be infectious by the time they are due to fly. Other individuals may become infected and develop COVID-19 symptoms by the time they fly, at which point they will either decide not to fly or choose to fly despite their symptoms. Other individuals may become infected in the days just prior to flying, at which point they are unlikely to present COVID-19 symptoms and are also unlikely to be infectious. Depending on the modelled post-arrival quarantine requirements, and passenger compliance with these requirements, this individual may spend all of their infectious days in the arrival community, be screened via testing, or decide to self-quarantine if they develop symptoms.

A4.2 Measure of infection risk

To measure the efficacy of the different testing strategies, we used the metric of *infectious days* screened from entering the community. This metric allows for a more comprehensive understanding of infection risk compared to measuring infectious individuals screened, including being able to take account of the following.

[74] Note that this methodology does not account for differing age and comorbidity structures across countries when estimating actual infection prevalence from reported cases.

- **Differing infectiousness levels for symptomatic and asymptomatic passengers.** Symptomatic and asymptomatic individuals have different durations of infectiousness. We modelled the median number of infectious days for symptomatic individuals as 7.1 days and for asymptomatic individuals as 5.3 days.
- **Infectious time that air passengers spend in their country of departure.** This metric accounts for the lower risk of infections from air passengers, who are unlikely to spend all of their infectious time in their destination country.

A4.3 Air passenger modelling assumptions

Model input	Description
Number of people intending to fly	Flight volumes from all travel corridor countries in July/August 2020.[75]
Departure countries	Travel corridor countries, July/August 2020.[76]
Duration of flight	Five hours, based on the average duration from the EU or other international destinations.
Proportion of infected passengers (prevalence estimates)	Based on prevalence of the passenger's departure region. Methodology from Russell et al. (2020) used to estimate under-ascertainment of SARS-CoV-2 cases. Underlying age/comorbidity structures and passenger demographics not considered[77]
Proportion of asymptomatic cases	3-55% - Beta(1.9, 6.3), Median: 0.21, IQR: (0.12, 0.32), 95%: (0.03, 0.55) – derived from quantile matching, 95%: (0.03, 0.55)[78]
Incubation period (i.e. time from exposure to onset of symptom)	Gamma(μ = 5.5, σ^2 = 6.5) Median: 5.1 days IQR: (3.6, 6.9) days 95%: (1.7, 11.5) days Derived from quantile matching with Median: 5.1 days, 97.5%: 11.5 days[79]
Infectious period	For symptomatic cases: Median: 7.1 days IQR: (5.7, 8.5) days 95%: (2.5, 11.6) days For asymptomatic cases: Gamma: (μ = 6, σ^2 = 12) Median: 5.3 days IQR: (3.5, 7.8) days

[75] Airport data 2020 05 | UK Civil Aviation Authority [Internet]. [cited 2020 4 July]. Available from: https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-Airport-data/Airport-data-2019/
[76] https://immigrationbarrister.co.uk/which-countries-are-exempt-from-the-uk-travel-quarantine/
[77] Timothy W Russell, Nick Golding, Joel Hellewell, Sam Abbott, Lawrence Wright, Carl A B Pearson, Kevin van Zandvoort, Christopher I Jarvis, Hamish Gibbs, Yang Liu, Rosalind M Eggo, John W Edmunds, Adam J Kucharski, Reconstructing the early global dynamics of under-ascertained COVID-19 cases and infections, medRxiv 2020.07.07.20148460; doi: https://doi.org/10.1101/2020.07.07.20148460
[78] Buitrago-Garcia DC, Egli-Gany D, Counotte MJ, Hossmann S, Imeri H, Ipekci AM, et al. The role of asymptomatic SARS-CoV-2 infections: rapid living systematic review and meta-analysis [Internet]. Epidemiology. medRxiv; 2020. Available from: https://www.medrxiv.org/content/10.1101/2020.04.25.20079103v2
[79] Lauer SA, Grantz KH, Bi Q, Jones FK, Zheng Q, Meredith HR, et al. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. Ann Intern Med [Internet]. 2020 5 May;172(9):577–82. Available from: http://dx.doi.org/10.7326/M20-0504

Model input	Description
	95%: (1.2, 14.4) days[80]
Symptomatic period (i.e. time after onset of symptoms until no longer symptomatic)	Gamma (μ = 9.1, σ^2 = 14.7) Median: 8.6 days IQR: (6.3, 11.3) days 95%: (3.2, 18.0) days Derivation based on moment matching distributions[81]
RT-PCR sensitivity	Modelled as a function of the time since their exposure by fitting a Generalised Additive Model (GAM), with a Binomial likelihood and penalised B-spline basis (P-spline), fitted to data collected by Grassly et al. (2020). As in Grassly et al. (2020), no assumptions are made on the relative sensitivity of RT-PCR tests for asymptomatic/symptomatic SARS-CoV-2 cases[82]
Antigen testing sensitivity	Antigen test sensitivity can vary significantly depending on the brand of test used, the population being tested, and the time-window post-infection that the test is administered. The test we use has the following reported sensitivities compared to PCR: • Pre-symptomatic: 80% • 0-7 days post-symptom onset: 95%[83] • 8+ days post-symptom onset: 80% • Asymptomatic: 80%

[80] Wölfel R, Corman VM, Guggemos W, Seilmaier M, Zange S, Müller MA, et al. Virological assessment of hospitalised patients with COVID-2019. Nature [Internet]. 2020 May;581(7809):465–9. Available from: http://dx.doi.org/10.1038/s41586-020-2196-x ;
Byrne AW, McEvoy D, Collins A, Hunt K, Casey M, Barber A, et al. Inferred duration of infectious period of SARS-CoV-2: rapid scoping review and analysis of available evidence for asymptomatic and symptomatic COVID-19 cases [Internet]. Epidemiology. medRxiv; 2020. Available from: https://www.medrxiv.org/content/10.1101/2020.04.25.20079889v1
[81] Quilty BJ, Clifford S, Flasche S, Eggo RM, CMMID nCoV working group. Effectiveness of airport screening at detecting travellers infected with novel coronavirus (2019-nCoV). Euro Surveill [Internet]. 2020 Feb;25(5). Available from: http://dx.doi.org/10.2807/1560-7917.ES.2020.25.5.2000080 ;
Li Q, Guan X, Wu P, Wang X, Zhou L, Tong Y, et al. Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia. N Engl J Med [Internet]. 2020 26 March;382(13):1199–207. Available from: http://dx.doi.org/10.1056/NEJMoa2001316
[82] https://www.thelancet.com/journals/laninf/article/PIIS1473-3099(20)30630-7/fulltext
[83]Pilarowski et Al., 'Field performance and public health response using the BinaxNOWTM Rapid SARS-CoV-2 antigen detection assay during community-based testing', 2020

Model input	Description
Air passenger quarantine compliance rate	We extrapolate data on air passenger quarantine compliance over time available from the ONS Survey and apply cumulative compliance values to quarantines with different durations. The survey reports: 72% of respondents definitely complying with quarantine by day 5, 71% of respondents definitely complying with quarantine by day 8, 58% of respondents complying by day 13.[84] We apply these quarantine compliance rates to both symptomatic and asymptomatic passengers.
Symptomatic quarantine compliance rate	In addition to being required to quarantine due to travel, individuals are also being asked to quarantine if they develop symptoms consistent with COVID-19 in most jurisdictions. Therefore, we include quarantining due to symptoms in our model as well. We set this at 18.2% for symptomatic individuals.[85] This is based on survey evidence in the UK population from King's College London.[86] This is applied to individuals both pre- and post- arrival in their travel destination.
Syndromic screening rate	18.2% of passengers symptomatic at the time of their flight decide not to travel, consistent with survey evidence from King's College London on symptomatic quarantine compliance.[87] As a sensitivity analysis a syndromic screening of 70% is included, reflecting early modelling on pre-departure screening.[88]

[84]ONS Survey on non-exempt passenger behaviour available from: https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/adhocs/12575nonexemptinternationalarrivalsselfisolationbehaviouralsurveypilotuk30septemberto8october2020

[85] Quilty BJ, Clifford S, Flasche S, Eggo RM, CMMID nCoV working group. Effectiveness of airport screening at detecting travellers infected with novel coronavirus (2019-nCoV). Euro Surveill [Internet]. 2020 Feb;25(5). Available from: http://dx.doi.org/10.2807/1560-7917.ES.2020.25.5.2000080 ;

[86] This has been updated from previously used international evidence based on the Norwegian population (based on a mix of individuals returning from international travel or being required to quarantine from contact tracing).

[87] This has been updated from previously used international evidence based on the Norwegian population (based on a mix of individuals returning from international travel or being required to quarantine from contact tracing).

[88] Gostic K, Gomez AC, Mummah RO, Kucharski AJ, Lloyd-Smith JO. Estimated effectiveness of symptom and risk screening to prevent the spread of COVID-19. Elife [Internet]. 2020 24 February;9. Available from: http://dx.doi.org/10.7554/eLife.55570

A5 List of countries considered in analysis[89]

The table below lists all of the countries considered in the analysis in section 4.3.

Table A5.1 Countries considered in analysis, where estimates of prevalence are available

Country count	Country name	Country code	Country count	Country name	Country code	Country count	Country name	Country code	Country count	Country name	Country code
1	AFGHANISTAN	AFG	37	EL SALVADOR	SLV	73	LESOTHO	LSO	109	ROMANIA	ROU
2	ALBANIA	ALB	38	EQUATORIAL GUINEA	GNQ	74	LIBERIA	LBR	110	RUSSIA	RUS
3	ALGERIA	DZA	39	ESTONIA	EST	75	LIBYA	LBY	111	SAUDI ARABIA	SAU
4	ANGOLA	AGO	40	ESWATINI	SWZ	76	LITHUANIA	LTU	112	SENEGAL	SEN
5	ARGENTINA	ARG	41	ETHIOPIA	ETH	77	LUXEMBOURG	LUX	113	SERBIA	SRB
6	ARMENIA	ARM	42	FINLAND	FIN	78	MADAGASCAR	MDG	114	SIERRA LEONE	SLE
7	AUSTRALIA	AUS	43	FRANCE	FRA	79	MALAWI	MWI	115	SINGAPORE	SGP
8	AUSTRIA	AUT	44	GABON	GAB	80	MALAYSIA	MYS	116	SLOVAKIA	SVK
9	AZERBAIJAN	AZE	45	GAMBIA	GMB	81	MALDIVES	MDV	117	SLOVENIA	SVN
10	BAHAMAS	BHS	46	GEORGIA	GEO	82	MALI	MLI	118	SOMALIA	SOM
11	BAHRAIN	BHR	47	GERMANY	DEU	83	MAURITANIA	MRT	119	SOUTH AFRICA	ZAF
12	BANGLADESH	BGD	48	GHANA	GHA	84	MAURITIUS	MUS	120	SOUTH KOREA	KOR
13	BELARUS	BLR	49	GREECE	GRC	85	MEXICO	MEX	121	SOUTH SUDAN	SSD
14	BELGIUM	BEL	50	GUATEMALA	GTM	86	MOLDOVA	MDA	122	SPAIN	ESP
15	BENIN	BEN	51	GUINEA	GIN	87	MONTENEGRO	MNE	123	SRI LANKA	LKA
16	BOLIVIA	BOL	52	GUYANA	GUY	88	MOROCCO	MAR	124	SUDAN	SDN
17	BRAZIL	BRA	53	HAITI	HTI	89	MOZAMBIQUE	MOZ	125	SURINAME	SUR
18	BULGARIA	BGR	54	HONDURAS	HND	90	NAMIBIA	NAM	126	SWEDEN	SWE
19	BURKINA FASO	BFA	55	HUNGARY	HUN	91	NEPAL	NPL	127	SWITZERLAND	CHE
20	CAMEROON	CMR	56	ICELAND	ISL	92	NETHERLANDS	NLD	128	TAJIKISTAN	TJK

[89] Based on availability of estimated prevalence data.

Country count	Country name	Country code	Country count	Country name	Country code	Country count	Country name	Country code	Country count	Country name	Country code
21	CANADA	CAN	57	INDIA	IND	93	NEW ZEALAND	NZL	129	THAILAND	THA
22	CENTRAL AFRICAN REPUBLIC	CAF	58	INDONESIA	IDN	94	NICARAGUA	NIC	130	TOGO	TGO
23	CHAD	TCD	59	IRAN	IRN	95	NIGER	NER	131	TUNISIA	TUN
24	CHILE	CHL	60	IRAQ	IRQ	96	NIGERIA	NGA	132	TURKEY	TUR
25	CHINA	CHN	61	IRELAND	IRL	97	NORTH MACEDONIA	MKD	133	UGANDA	UGA
26	COLOMBIA	COL	62	ISRAEL	ISR	98	NORWAY	NOR	134	UKRAINE	UKR
27	COSTA RICA	CRI	63	ITALY	ITA	99	OMAN	OMN	135	UNITED ARAB EMIRATES	ARE
28	CROATIA	HRV	64	JAMAICA	JAM	100	PAKISTAN	PAK	136	UNITED KINGDOM	GBR
29	CUBA	CUB	65	JAPAN	JPN	101	PANAMA	PAN	137	UNITED STATES OF AMERICA	USA
30	CYPRUS	CYP	66	JORDAN	JOR	102	PARAGUAY	PRY	138	URUGUAY	URY
31	CZECHIA	CZE	67	KAZAKHSTAN	KAZ	103	PERU	PER	139	UZBEKISTAN	UZB
32	DENMARK	DNK	68	KENYA	KEN	104	PHILIPPINES	PHL	140	VENEZUELA	VEN
33	DJIBOUTI	DJI	69	KUWAIT	KWT	105	POLAND	POL	141	VIETNAM	VNM
34	DOMINICAN REPUBLIC	DOM	70	KYRGYZSTAN	KGZ	106	PORTUGAL	PRT	142	YEMEN	YEM
35	ECUADOR	ECU	71	LATVIA	LVA	107	PUERTO RICO	PRI	143	ZAMBIA	ZMB
36	EGYPT	EGY	72	LEBANON	LBN	108	QATAR	QAT	144	ZIMBABWE	ZWE

A6 Sensitivity analysis of travel corridor countries at current prevalence levels

As a sensitivity analysis, we have also estimated the number of green and amber list countries, assuming that country prevalence remains the same as it is currently estimated to be (as of 14 March 2021). We have compared 14 March 2021 prevalence to the prevalence thresholds for May/June. We then calculated the number of countries where travel corridors could be created, or travel with pre-departure/on-departure testing could be introduced, without changing the relative COVID-19 risk to the UK (compared to previous travel corridors).

This is a very conservative estimate as prevalence tends to be lower in July/August (particularly in the Northern Hemisphere). This is because more socialising occurs outdoors in the summer, making it easier to socially distance.

Table A6.1 Travel corridor sensitivity analysis using current prevalence thresholds

Travel re-open date	Prevalence threshold	Testing scheme	Countries with risk equalised
17 May 2021	0.13%	No testing or quarantine	78 of 143 or 55%
	0.24%	PCR 72 h pre-departure	90 of 143 or 62%
	0.35%	Antigen on departure	103 of 143 or 72%
21 June 2021	0.10%	No testing or quarantine	70 of 143 or 49%
	0.18%	PCR 72 h pre-departure	84 of 143 or 59%
	0.27%	Antigen on departure	98 of 143 or 69%

A7 Decrease in domestic risk from air passengers for three example markets

Taking average estimated prevalence levels from July/August 2020 as our baseline prediction for prevalence levels after 21 June 2021, we estimated how domestic COVID-19 risk from air passengers would decrease for three example markets: Spain, Turkey and the USA.

Using assumptions already outlined in sections 3.3 and 4.3,[90] we estimated decreases in secondary hospitalisation and death risk from air passengers as vaccines are rolled out. We modelled this assuming no testing or quarantine requirements (see Table A7.1).

For all countries,[91] we estimated that air passenger prevalence from these countries is set to decrease by 26%, secondary infections are set to decrease by 39%, hospitalisations are set to decrease by 80%, and deaths are set to decrease by 90%.

[90] We use the combination of estimated decreases in air passenger prevalence due to UK vaccine immunity and domestic decreases in R_t, hospitalisation risk and death risk to calculate how secondary hospitalisations and deaths resulting from infections transmitted from air passengers are likely to decrease as vaccinations are rolled out.
[91] Proportional decreases are the same as we apply the same assumptions around vaccines to all origin countries.

Table A7.1 Decrease in domestic COVID-19 risk from air passengers for example markets, as of 21 June 2021

		Air passenger prevalence	Infectious days (per 1m travellers)	Rt	Secondary infections	Hospitalisations	Deaths
Spain	2020 (No testing/ quarantine requirements)	0.21%	6399.3	0.9	752.0	39.9	5.6
	2021[92] (No testing/ quarantine requirements)	0.16%	4709.9	0.7	458.0	9.7	0.5
	Absolute difference	**-0.06%**	**-1689.4**	**-0.1**	**-294.0**	**-30.2**	**-5.1**
Turkey	2020 (No testing/ quarantine requirements)	0.034%	1019.7	0.9	119.8	6.4	0.9
	2021 (No testing/ quarantine requirements)	0.025%	750.5	0.7	73.0	1.6	0.1
	Absolute difference	**-0.01%**	**-269.2**	**-0.1**	**-46.9**	**-4.8**	**-0.8**
USA	2020 (No testing/ quarantine requirements)	0.51%	15250.7	0.9	1792.1	95.1	13.2
	2021 (No testing/ quarantine requirements)	0.38%	11224.5	0.7	1091.4	23.2	1.1
	Absolute difference	**-0.13%**	**-4026.2**	**-0.1**	**-700.7**	**-71.9**	**-12.1**

[92] 2021 figures are estimated by scaling July/August average prevalence by the proportion of UK air passengers immune through vaccinations (i.e. 60% of terminal passengers are UK residents, 44% of which are projected to be immune by 21 June 2021).

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