Modelling the effectiveness of airport testing regimes

Prepared for
Virgin Atlantic, IAG, TUI, Heathrow, MAG, Collinson, Airlines UK and IATA

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Executive summary

Since June 2020, the UK has required all international travellers to the UK, except those arriving from a list of exempt ('travel corridor') countries, to quarantine for 14 days. Unlike several other countries, the UK has not introduced any scheme to test travellers for COVID-19. We understand that part of the basis for this policy is evidence presented in a paper by Public Health England (PHE) that concluded testing on arrival at an airport would identify only 7% of virus cases and so would not be effective at helping to control the spread of COVID-19.[1]

Oxera and Edge Health, with input from Dr Kit Yates, were commissioned by a consortium of airlines, airports and industry organisations to undertake a review of the PHE paper, as well as two other studies on the effectiveness of testing schemes—one from the London School of Hygiene & Tropical Medicine (LSHTM)[2] and one from the Animal and Plant Health Agency (APHA).[3] This review identified areas where the existing modelling could be improved.[4]

We also considered real-world evidence from testing schemes in place at airports around the world, including Jersey, Canada (Toronto-Pearson Airport), France (Paris-Charles de Gaulle Airport, CDG) and Iceland. Our analysis found that testing on arrival regimes are able to identify between 54% and 76% of infected travellers, and that testing after five and seven days produces nearly identical results in terms of effectiveness (between 83% and 90% and 84% and 90% respectively).[5]

This report presents the results from our own modelling of the effectiveness of airport testing regimes and sets this in the context of the real-world evidence. In our modelling we use the LSHTM model as a starting point, but make a number of significant changes, as follows.

1. We introduce non-compliance with quarantine restrictions to reflect new evidence on reported behaviours. While the latest survey evidence from Anneke et al. (2020)[6] finds that compliance is 71% for symptomatic individuals, it is 28% for asymptomatic individuals. This is consistent with similar findings on compliance reported by SAGE.[7]

2. We update the sensitivity of Reverse Transcription Polymerase Chain Reaction (hereafter RT-PCR) testing to reflect a review by Grassly et al. (2020)[8] that suggests a higher peak test sensitivity than used in the LSHTM model.

[1] Public Health England (2020), 'Investigation into the effectiveness of 'double testing' travellers incoming to the UK for signs of COVID-19 infection', 17 June.
[2] Clifford et al. (2020), 'Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers', 25 July.
[3] Taylor, R.A. et al. (2020), 'The risk of introducing SARS-CoV-2 to the UK via international travel in August 2020', 9 September.
[4] See Oxera and Edge Health (2020), 'Review of evidence on testing on arrival schemes', 22 October.
[5] See Oxera and Edge Health (2020), 'Review of case studies of effectiveness of testing schemes', 2 November.
[6] Steens A, et al (2020), 'Poor self-reported adherence to COVID-19-related quarantine/isolation requests, Norway, April to July 2020', 17 September. Volume 25, Issue 37. Available at: https://doi.org/10.2807/1560-7917.ES.2020.25.37.2001607
[7] Scientific Advisory Group for Emergencies (2020), 'Multidisciplinary Task and Finish Group on Mass Testing', 11 September, para 9.
[8] Grassly, Nicholas C et al., (2020), 'Comparison of molecular testing strategies for COVID-19 control: a mathematical modelling study', The Lancet Infectious Diseases, 18 August.

3. In line with Grassly et al. (2020), we assume that testing sensitivity for asymptomatic individuals is similar to that for symptomatic individuals.

4. We consider Reverse Transcription Loop-mediated Isothermal Amplification (hereafter RT-LAMP) testing as an alternative to RT-PCR that is comparable in sensitivity and with results that can be delivered within 30–60 minutes, and therefore has significant practical and logistical benefits. Antigen testing is outside the scope of this analysis but may warrant further investigation in future.

5. We update prevalence rates and flight volumes to reflect recent data from August 2020. We use August as it is the most recent month where data is available and it reflects a period when infections were generally considered to be manageable.

6. We model the effectiveness of pre-departure testing schemes, although at present we do not have the real-world data that we have for arrival testing in order to calibrate the outputs. Trial evidence for pre-departure testing effectiveness is an area where more data would be valuable.

The outputs from this updated modelling suggest that a single test on arrival would catch around 60% of infectious travellers,[9] far higher than PHE's 7% estimate, and above LSHTM's (45%) and APHA's (40%) estimates of effectiveness. This result is also in line with the evidence from the Jersey and Iceland case studies considered.

To put the results of our modelling for on arrival testing in context, we consider how many potential infectious passengers may enter the UK population if there is a testing on arrival scheme in place, as follows:[10]

- Consider 6,871 air passengers that travelled to the UK from the USA in a given week in August 2020;[11]
- Using prevalence rates in the USA in August, we estimate that 33 people that intended to travel to the UK would have been infected with COVID-19;
- Of these 33 people, we estimate that 19 would not have travelled due to experiencing symptoms of COVID-19, would quarantine upon arrival due to symptoms, or would no longer be infectious upon arrival, leaving 14 infectious passengers potentially entering the community;
- Of these 14 infectious passengers, eight would have been identified with arrival testing leaving six infectious passengers entering the UK with an infection that had not been detected;
- Therefore six people from the 6,871, or 0.09% of air passengers, may have been infectious and entered the UK. This is equivalent to nine infectious passengers per 10,000 passengers. In England the ONS estimated that there has been an infection prevalence of 57 per 10,000 people over September and October.[12] We also note that based on the current UK government policy, there may be some infectious passengers entering the

[9] See section 4, Table 4.2 for a comparison of infected travellers screened (100% compliance framework) with real-world evidence.
[10] These figures also assume full compliance with quarantine to be able to compare to the previous analysis undertaken.
[11] This is based on scaling average 2019 flight volumes from the USA by August 2020 data.
[12] See: https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/datasets/coronaviruscovid19infectionsurveydata, accessed Nov 4th 2020

UK population from travel corridor countries, as no tests or quarantine period are required for these passengers.

In addition to considering a single test on arrival, we expand the current evidence base by modelling the effectiveness of different testing regimes and technologies, including:

- three days before departure (RT-PCR and RT-LAMP);
- on departure (RT-LAMP);
- on arrival (RT-PCR and RT-LAMP);
- one to eight days after arrival (RT-PCR and RT-LAMP).

For each of these cases, we consider the results if there is full compliance with quarantine periods and where compliance is in line with the latest available evidence on individual behaviour (28% for non-symptomatic individuals and 71% for symptomatic individuals).

We model both the number of **infected passengers** who enter society and the number of **infectious days** that these infected travellers spend in the community. The latter is our preferred measure since it enables us to capture the changing risk of infection spread as passengers change their compliance levels (upon developing symptoms or receiving a positive test). Infected passengers screened are thus only considered for the 100% compliance scenario.

In the scenarios with full compliance, we find that five-day RT-PCR testing regimes are nearly as effective as a 14-day quarantine. However, when non-compliance is introduced, 14-day quarantine yields the highest number of infectious days released, and is therefore the least effective strategy.

In the scenarios where we consider non-compliance with quarantine, infectious days are minimised with a test on day three. This reflects the balance between infection detectability increasing while travellers wait for a test and an earlier testing minimising non-compliant days for passengers who receive a positive test result. In the scenarios where we consider non-compliance with quarantine, we also find that on arrival testing would be twice as effective as the current quarantine policy.

Our analysis is based on new information and evidence that has recently become available. In addition, it extends the work undertaken to date by incorporating evidence on non-compliance with current quarantine requirements. This necessitates a focus on infectious days, which allows for changing compliance levels to be accounted for. Developing a better understanding of infection risk in the context of non-compliance is critical in considering different public health policies.

1 Introduction

Oxera, Edge Health, and Dr Kit Yates[13] were commissioned by Virgin Atlantic, IAG, TUI, Heathrow, MAG, Collinson, Airlines UK and IATA to undertake independent modelling on the effectiveness of testing schemes for international travellers.

This report summarises our modelling and builds on our two previous reports:

- Oxera and Edge Health (2020), 'Review of evidence on testing on arrival schemes', 22 October. In this report, we reviewed the literature on the effectiveness of testing on arrival schemes, including papers from PHE, LSHTM and APHA.
- Oxera and Edge Health (2020), 'Review of case studies of effectiveness of testing schemes', 29 October. In this report, we considered the effectiveness of testing schemes in other jurisdictions: Jersey, Canada (Toronto-Pearson Airport), France (Paris-CDG) and Iceland.

Our first report concluded that the key finding of the PHE analysis that testing on arrival would identify only 7% of virus cases is significantly understated. This 7% assumes that all infected travellers who are symptomatic or detectable with a test on departure do not board flights to the UK and therefore only travellers who become detectable during the course of their flight are included in the 7%.

We also concluded that there are a number of areas where the current evidence base supporting the policy for quarantine rather than a testing scheme should be improved. In particular, the papers did not adequately consider non-compliance with quarantine, and many of the assumptions were not based on the most recent empirical evidence. The findings from our first report have informed our modelling decisions and inputs in this report.[14]

We also noted that it is important that outputs of theoretical models are calibrated with real-world evidence from established airport testing regimes. In our second report we therefore reviewed the effectiveness of four testing schemes in place around the world. We found that the effectiveness of a testing on arrival scheme is between 54% and 76%. Our analysis of these testing schemes also showed that testing after five days is between 83% and 90% effective, with testing after seven days showing nearly identical results of between 84% and 90%. We have used the results of this second report to benchmark our modelling outputs.[15]

The outputs of this report are intended to feed into the work of the Global Travel Taskforce as it considers how a testing regime for international arrivals could be implemented to safely re-open international travel at scale to and from the UK.

The rest of this report is structured as follows:

- section 2 sets out our methodology;
- section 3 provides the results of our analysis;

[13] Dr Kit Yates is a Senior Lecturer in mathematical biology and Co-director of the Centre for Mathematical Biology at the University of Bath
[14] See section 2 and Appendix A1 for more details on key assumptions.
[15] See section 4.

- section 4 compares these results with real-world evidence;
- section 5 concludes.

The appendices provide more detail on the results of our analysis and the sensitivity analysis undertaken.

2 Methods

To undertake our analysis, we have built on the model developed and shared by LSHTM.[16] This model provides a good starting point and allows us to include a number of updated assumptions to reflect the findings from our first report, and new evidence that help improve the understanding of the effectiveness of different approaches.

The key assumptions that we identified and have updated include:

- flight volume and prevalence data;
- testing sensitivity, including consideration of different testing technologies (RT-PCR and RT-LAMP), with their respective sensitivities and turnaround times, and testing sensitivity for asymptomatic passengers;
- non-compliance with quarantine requirements.

Due to data constraints we have not considered the impact of differing demographics in the air passenger population that might lead to differing COVID-19 infection levels in the passenger population. If infection rates were corrected for demographics, we would expect passenger prevalence to be lower than that of the general population.[17] (We use the methodology from the LSHTM paper to estimate prevalence, which does not account for differences in age/comorbidity structures when estimating prevalence from deaths data.

In Appendix A1, we outline the input assumptions to this model and their respective sources.

The testing strategies that we consider in our analysis, along with descriptions of the key input assumptions that we have updated, are set out in sections 2.1 to 2.6 below.

2.1 Model framework

In this report, we evaluate the effectiveness of different testing schemes and quarantine policies at preventing individuals infected with COVID-19 from entering the community and spreading the infection in the UK population after arriving from abroad. We focus on passengers arriving in the UK from the EU and the USA. We consider the infection status of these travellers and, for those who are infected, their infection evolution (e.g. whether an individual will become symptomatic, how long their infectious period will last).

We then consider different risk mitigation strategies (as outlined in section 2.3) and evaluate their effectiveness by calculating two metrics: the number of infectious individuals released into the community, and the number of remaining infectious days released into the community by these individuals. We focus on infectious days in the results section (section 3) and calculate infectious individuals screened mainly to compare modelling outputs with the real-world evidence in section 4 (see section 2.6 for a full explanation of evaluation metrics).

[16] This is available at the following link: https://github.com/cmmid/travel_screening_strategies

[17] This is because the income level of travellers would on average be higher than that of a general population and the evidence suggests that high COVID-19 prevalence correlates with deprivation

2.2 Infectious travellers

Each month, a certain number of passengers will travel between the UK and the EU or the USA. To estimate the number of passengers who will travel in the coming months, we use average 2019 passenger volumes, and scale these to reflect the reduction in flight volumes between August 2019 and August 2020.[18] To estimate the number of weekly inbound travellers, we assume an equal amount of inbound and outbound travel, as in the LSHTM paper.[19]

To estimate the proportion of intended inbound travellers that could be infected with COVID-19, we calculate the estimated prevalence for 10 August for the USA and EU using methodology outlined by Russell et al. (2020).[20]

In line with the LSHTM paper, we make distributional assumptions about the percentage of the traveller population who are asymptomatic (between 3% and 55%).[21] We then model the infection evolution timeline for each infected passenger (see Appendix A1 for all relevant assumptions).

Table 2.1 Traveller volume and infection assumptions

	EU	USA
Average monthly traveller movements,[22] from 2019[23]	14,184,974	1,848,557
Year-on-year change for August 2020 compared to August 2019 (%)[24]	0.247	0.031
Calculated total traveller volume August 2020 using August year-on-year change, n [25]	3,512,219	58,829
Duration of typical flight (hours)	2	8
Prevalence of SARS-CoV-2 on 10 August 2020[26]	5.7 per 10,000	49.8 per 10,000
Number of infected individuals intending to travel in a given week. Median and 95% interval from 1,000 simulations	Symptomatic: 180 (113, 246) Asymptomatic: 48 (8, 119)	Symptomatic: 25 (8, 49) Asymptomatic: 7 (1, 21)

Source: Edge Health and Oxera.

2.3 Risk mitigation strategies

We focus our analysis on one-test strategies, where a test is administered at one of the following times:

[18] CAA 'Airport data 2019.' Available at: https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-Airport-data/Airport-data-2019-07/
[19] Weekly inbound travellers are estimated by sampling from a binomial distribution $W \sim Bin(p = 7/30, \lceil n/2 \rceil)$, where n is the monthly number of travellers moving between the UK and EU or the USA.
[20] Russell, T. W. et al., (2020), 'Reconstructing the early global dynamics of under-ascertained COVID-19 cases and infections', 22 September, medRxiv. Available at: https://doi.org/10.1101/2020.07.07.20148460
[21] Buitrago-Garcia DC, et al., (2020), 'The role of asymptomatic SARS-CoV-2 infections: rapid living systematic review and meta-analysis, 28 July, medRxiv. Available at: https://www.medrxiv.org/content/10.1101/2020.04.25.20079103v3.
[22] Traveller movements include both outbound and inbound journeys
[23] CAA 'Airport data 2019.' Available at: https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-Airport-data/Airport-data-2019-07/
[24] Calculated by dividing August 2020 traveller volumes from https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-Airport-data/Airport-data-2019-07/ with August 2019 volumes from the same source.
[25] Calculation, using 12 and 13 as inputs.
[26] Russell, T. W. et al., (2020), 'Reconstructing the early global dynamics of under-ascertained COVID-19 cases and infections', 22 September, medRxiv. Available at: https://doi.org/10.1101/2020.07.07.20148460

- three days prior to departure;
- on departure;
- on arrival;
- one, two, three, four, five, six, seven or eight days after arrival (delayed arrival testing).

In the departure testing scenario, passengers are required to self-isolate after their test for three days until their departure. In delayed arrival testing scenarios (with delays of between one and eight days), passengers are required to quarantine until they are tested and receive a negative test result.

All of the above scenarios are benchmarked against a baseline where no testing is required, and an individual is free to enter the community straight after their arrival. For comparison, we also considered the current policy under which no testing is performed, but an individual is required to quarantine for 14 days after their arrival.

In line with the LSHTM paper, we assume that, in all of the scenarios, 70% of passengers who are symptomatic at departure would not board their flight due to being detected through syndromic screening at the airport or because they chose not to fly in line with airline guidance.[27] In all scenarios (including the baseline), we assume that if a passenger develops symptoms at any point in time, they begin an additional quarantine period of at least seven days from symptom onset until they no longer experience symptoms or it has been at least 14 days since their arrival in the country (whichever quarantine period is longest).

We evaluate the efficacy of the testing regimes above using two different frameworks: one assuming 100% compliance with the aforementioned quarantine policies (full compliance), and the other assuming varying compliance rates for symptomatic, asymptomatic and pre-symptomatic cohorts of passengers (see section 2.5 for a full explanation).

2.4 Testing technologies and detection models

We consider two testing technologies currently used to detect a SARS-CoV-2 infection: RT-PCR and RT-LAMP. While RT-PCR testing appears to be the current diagnostic standard, with many countries introducing a requirement for travellers to undergo testing for SARS-CoV-2 using this method, it is not without its limitations. It is difficult to use RT-PCR for mass testing as transporting the samples to laboratories imposes extensive logistical constraints and introduces high transportation costs. The necessity for the samples to be processed in laboratories also means that it takes at least 24 hours for the sample to be collected, transported, and processed, and for the outcome to be communicated to the person tested.

RT-LAMP testing presents an attractive alternative for identifying infected individuals. Unlike RT-PCR, it can be performed outside of sophisticated diagnostic laboratories and with a much quicker turnaround time (less than one hour). Additionally, the process of sample collection is much simpler for RT-LAMP testing and does not require a trained healthcare professional to be present to ensure that it is administered correctly. When it comes to sensitivity,

[27] Clifford et al. (2020), 'Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers', 25 July.

RT-LAMP testing is similar or marginally less accurate than RT-PCR testing.[28,29]

In our modelling, we explored the efficacy of using these two testing technologies to identify infected individuals arriving from abroad. We assume that it takes one day to process an RT-PCR test and that a tested individual should quarantine while awaiting their results. We assume that the results of RT-LAMP testing are instantaneous, and hence no quarantining is required.[30]

We model RT-PCR test sensitivity as a function of the time since an individual's exposure to COVID-19 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), we make no assumptions on the relative sensitivity of RT-PCR tests for asymptomatic/symptomatic SARS-CoV-2 cases.[31] We also assume the same sensitivity for self-administered tests (pre-departure and delayed arrival testing) and tests administered by healthcare professionals (on-departure and on-arrival testing). We apply a scaling factor for the relative effectiveness of RT-LAMP testing (0.9) compared to RT-PCR testing to the RT-PCR test sensitivity distribution.[32]

Table 2.2 summarises the combinations of test administration times, testing technologies, and minimum quarantine periods.

Table 2.2 Testing strategies considered

Group	Timing of administering test	Testing technology	Minimum quarantine period[33]
Baseline	None	None	None
14-day quarantine	None	None	14 days
Pre-departure	Three days pre-departure	RT-PCR RT-LAMP	None, quarantine in country of origin
	At airport, on departure	RT-LAMP	None
On arrival	At airport, on arrival	RT-PCR RT-LAMP	One day None
Post-arrival	One to eight days post-arrival	RT-PCR RT-LAMP	Two to nine days One to eight days

Source: Edge Health and Oxera.

[28] Zhang et al. (2020), 'Rapid Molecular Detection of SARS-CoV-2 (COVID-19) Virus RNA Using Colorimetric RT-LAMP', 29 February.
[29] Yokota et al. (2020), 'Mass screening of asymptomatic persons for SARS-CoV-2 using saliva', 15 August.
[30] While this is not necessarily true, a person tested using RT-LAMP technology would be able to receive their results without leaving the testing facility (e.g. airport) and hence will not impose any infectious risk to the community.
[31] As in Grassly et Al., 2020, 'we did not include differing test sensitivity by symptoms because estimates of the proportion of infections that are asymptomatic are largely based on RT-PCR testing (in practice, this means that infections with a very low viral load that may not be detected and are unlikely to contribute to transmission are not included) and because of uncertainty about the extent of viral shedding from asymptomatic compared with symptomatic individuals.'
[32] The scaling factor was derived from the data presented by Yokota et al. (2020) 'Mass screening of asymptomatic persons for SARS-CoV-2 using saliva', 15 August. Out of the 44 positive samples collected by the researchers, four samples were negative by RT-LAMP test and positive by RT-PCR; hence we assume the relative sensitivity to be 0.9.
[33] If individuals become symptomatic or test positive for SARS-CoV-2, their quarantine period may be extended.

2.5 Compliance rates

Until now, most of the research evaluating risk mitigation strategies has assumed a high level of compliance with quarantine restrictions. In the PHE and LSHTM papers, 100% of arriving passengers were assumed to comply with quarantine requirements. In the APHA paper, 80% of arriving passengers were assumed to comply with quarantine requirements. This high level of compliance is not in line with academic research on compliance and significantly inflates the efficacy of quarantine regimes.

Recent surveys[34] have shown that 71% of symptomatic and 28% of asymptomatic individuals comply with quarantine/isolation requirements; we have used these figures as inputs for our modelling.[35] Another survey of the UK population suggests that test-and-trace quarantine compliance may be even lower, with as few as 18% of people reporting that they quarantined after developing symptoms consistent with COVID-19.[36] It is therefore essential to take non-compliance rates into account when modelling the outcomes of different risk mitigation scenarios. For this reason, we use two different compliance frameworks for our model.

The first framework—*full compliance*—assumes 100% compliance with the imposed quarantine policies. While potentially unrealistic, this framework produces outputs that are directly comparable with the findings from the research conducted previously. In this framework, we assume 100% compliance extends to the following quarantine periods: between pre-departure testing and departure, while waiting to be tested after arrival, while displaying symptoms consistent with COVID-19 after arrival..

The second framework—*non-compliance*—makes the following assumptions about non-compliance for different cohorts of passengers.[37]

- **Quarantine compliance:** an individual will be compliant with quarantine policies with a probability of 0.28 (this includes the requirement to quarantine between pre-departure test and departure in a pre-departure testing scenario, the requirement to quarantine for 14 days in the current policy and the requirement to quarantine until a negative test result is received in a delayed arrival testing scenario). Note that this compliance rate is consistent with individuals being pre-symptomatic or asymptomatic at the time the quarantine requirement begins.
- **Symptoms compliance** (does not apply for asymptomatic passengers): an individual who is symptomatic will be compliant with quarantine policies with a probability of 0.71 (this is a requirement for symptomatic people to enter a quarantine of at least seven days after the onset of symptoms and to stay in

[34] Based on Norwegian population. Compliance was defined in this study as having complied with quarantine requirements for at least one day. Quarantine requests for travel reasons or because of being contacts/household members of positive case were pooled. We use this survey data as it includes respondents who are requested to quarantine due to travel. This evidence also allows us to differentiate between asymptomatic/pre-symptomatic compliance and symptomatic compliance.
[35] Steens A, et al (2020), 'Poor self-reported adherence to COVID-19-related quarantine/isolation requests, Norway, April to July 2020', 17 September. Volume 25, Issue 37. Available at: https://doi.org/10.2807/1560-7917.ES.2020.25.37.2001607.
[36] Smith, L.E. et al. (2020), 'Adherence to the test, trace and isolate system: results from a time series of 21 nationally representative surveys in the UK (the COVID-19 Rapid Survey of Adherence to Interventions and Responses [CORSAIR] study)' Preprint, 18 September. Available at: https://www.medrxiv.org/content/10.1101/2020.09.15.20191957v1.full.pdf
[37] Steens A, et al (2020), 'Poor self-reported adherence to COVID-19-related quarantine/isolation requests, Norway, April to July 2020', 17 September. Volume 25, Issue 37. Available at: https://doi.org/10.2807/1560-7917.ES.2020.25.37.2001607.

quarantine until they are no longer symptomatic and have been in the country for 14 days).

- **Test compliance:**[38] an individual who receives a positive test result will be compliant with quarantine policies with a probability of 1 (this is the requirement for a person who tested positive to quarantine for 14 days from the day they were tested).

We assume that passengers who are not compliant with quarantine rules are released into the community as soon as they arrive in the UK (and will be counted as a released infection if they are infectious at the time). As asymptomatic passengers never develop symptoms, only the quarantine compliance and test compliance apply to this group.

Based on the compliance levels outlined above, symptomatic passengers will fall into one of the following categories:

- quarantine and symptoms compliant: they will follow the quarantine guidelines upon arrival (if any) and will quarantine if they develop symptoms outside of the mandatory quarantine period;
- quarantine and symptoms non-compliant: they will not follow the quarantine guidelines upon arrival and will not start a quarantine even if they develop symptoms;
- quarantine non-compliant and symptoms compliant: they will not quarantine upon arrival when required, but will revert back to quarantine if they develop symptoms;
- quarantine compliant and symptoms non-compliant: they will quarantine for as long as they are asked to when they arrive, but if they develop symptoms, they will not start the second quarantine period.

Passengers from all four of the above groups will go into quarantine for 14 days if they receive a positive test result.

2.6 Evaluation metrics

We evaluate each scenario in two compliance frameworks using two main metrics: infections screened, and infectious days screened.

2.6.1 Infections screened

Each individual who is still infectious when released into the community after receiving a false negative test result, finishing their quarantine period, or not following quarantine rules due to non-compliance, is counted as a released infection regardless of whether they enter a quarantine period later on (e.g. due to developing symptoms or receiving a positive test result).

The outputs from this metric can be compared to the outputs from research undertaken previously (assuming 100% compliance). It can also be compared

[38] Compared to the current 14-day quarantine policy, ensuring compliance will be considerably easier with a much smaller cohort of passengers who test positive. Currently there is limited enforcement of quarantine restrictions (from 8 June to 7 September, 34 fixed penalty notices for breaches of international travel measures were issued in the UK). See: Border Force (2020), 'Data on health measures at the UK border', 10 September. Available at: https://www.gov.uk/government/publications/data-on-health-measures-at-the-uk-border/data-on-healthmeasures-at-the-uk-border, accessed October 15, 2020.

to the real-world evidence outlined in our earlier review of testing schemes in Jersey, Toronto-Pearson Airport, Paris-CDG and Iceland.[39]

While the outputs from this metric are easy to interpret and convey the effects of different risk mitigation scenarios in a full compliance framework, they will not show the full picture in the non-compliance framework. For example, an individual in a delayed arrival testing scenario, who is quarantine non-compliant, is released into the community on arrival but reverts back into quarantine upon receiving a positive test result on day two, will be counted as a released infection. At the other end of the spectrum, an individual in the baseline scenario, who is quarantine non-compliant and infectious for 14 days after arrival will be counted as a released infection. It can be argued that the latter poses a higher infectious risk than the former, as they will have the opportunity to spread the infection in the community for seven times more days.[40]

Therefore, we only consider infectious individuals screened for the full compliance framework (see Tables 3.1 and 4.2). For the non-compliance framework, we consider the number of infectious days released into the community rather than infectious individuals screened (see section 3.2).

2.6.2 Infectious days screened

Through modelling each individual's infection evolution, we can estimate how many infectious days they have remaining when they arrive in the UK. This metric provides a better view of different scenarios' effectiveness at reducing infection spread once non-compliance is introduced, as it accounts for changing compliance levels upon receipt of a positive test or upon developing symptoms.

Depending on the scenario considered and an individual's compliance state, an individual will enter zero, one or two quarantine periods after their arrival. We calculate the number of infectious days released into the community for each individual by summing up the number of days an individual was not in quarantine while being infectious. This includes:

- the time after their arrival and before they enter a quarantine period (e.g. the time between arrival and receiving a positive test result for quarantine non-compliant individuals);
- the time between the end of the first quarantine period and the beginning of the second (e.g. the time between receiving a false-negative test result on day three and developing symptoms and entering the second quarantine period on day five for quarantine and symptoms compliant individuals);
- the time between the end of the quarantine period and the end day of infectiousness (e.g. the time between being released after a false-negative test on arrival and stopping being infectious on day four).

[39] With a few caveats around the different calculation methods for the effectiveness of passenger screening regimes, our methodology compares the effectiveness to a baseline that includes compliance with quarantine measures should travellers become symptomatic, while the real-world evidence evaluates infected travellers identified via testing compared to the total incoming infected travellers (estimation of total incoming infected travellers varies based on data availability).
[40] Caveated by evidence that (generally speaking) individuals have the highest viral load (and are thus most infectious) after the first few days of developing symptoms (for symptomatic cases).

3 Results

We compare the effectiveness of different passenger screening schemes in both full compliance and non-compliance quarantine frameworks. Passenger screening schemes are compared to syndromic screening at departure alone, without quarantine or testing requirements (as outlined in section 2.3). While evidence suggests that non-compliance with quarantine is more reflective of current behaviours, the full compliance framework is used for comparison to previous analysis undertaken.

We present both infectious individuals and infectious days screened for the full compliance framework. For the non-compliance framework, we present infectious days. This allows us to account for possible changes in passengers' quarantine compliance, as outlined in section 2.6.

In section 4, where we compare our modelling outputs with our previous analysis on real-world evidence, we use the percentage of passengers screened from the full compliance framework. In section 5, we contextualise the percentage of passengers screened in the full compliance framework in terms of absolute values of infectious passengers.

Key post-arrival passenger screening strategies are presented in this section. For all post-arrival schemes, see Appendix A1 (which includes testing delays ranging from one to eight days).

3.1 Infectious individuals screened

In the full compliance framework, 58% of infectious individuals are screened out by on-arrival testing using RT-PCR technology and 47% of infectious individuals are screened out by on-arrival testing using RT-LAMP technology. RT-PCR screens a higher proportion of passengers as it is assumed to be more sensitive than RT-LAMP testing. In addition, for certain cohorts of passengers who have false negative results, additional quarantine requirements for RT-PCR testing (delay of one day while waiting for results) will mean that there will be some individuals who will stop being infectious while waiting for their test results (while their counterparts in RT-LAMP testing scenario would be released straight away while still being infectious). This also contributes to a gap in effectiveness between RT-PCR and RT-LAMP testing scenarios.

In the full compliance framework, similar proportions of infectious individuals are screened in the three-, five-, and seven-day scenarios compared to the baseline 14-day quarantine scenario. Using RT-PCR, a median of 89% (three-day), 94% (five-day) and 95% (seven-day) of infectious travellers are detected. Using RT-LAMP, a median of 83% (three-day), 90% (five-day) and 93% (seven-day) of infectious individuals are screened out, respectively. The marginal benefit of the seven-day policy compared to the five-day policy is minimal, suggesting that the additional days of quarantine may not result in additional infectious travellers identified.

In the full compliance framework, the test three days before departure performs relatively well, screening 69% of infections (using RT-PCR) and 67% of infections (using RT-LAMP). This is in part because of the requirement to quarantine for the three days after being tested, which means that passengers who may otherwise have been exposed to the virus in the three days prior to flying would no longer be exposed. When we consider the non-compliance scenario, the relative effectiveness of this scheme decreases.

Table 3.1 Percentage of travellers identified via screening schemes (full compliance framework)

Group	Description	Percent of infectious travellers screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	95% (88%, 100%)	95% (88%, 100%)
Pre-departure	Test three days before departure	67% (55%, 79%)	69% (57%, 81%)
	Test on departure	47% (32%, 60%)	NA
On arrival	Test on arrival	47% (31%, 60%)	58% (41%, 70%)
Post-arrival	Test three days after arrival	83% (71%, 92%)	89% (79%, 96%)
	Test five days after arrival	90% (81%, 98%)	94% (86%, 100%)
	Test seven days after arrival	93% (84%, 100%)	95% (87%, 100%)

Note: Median values are presented, along with 90% confidence intervals.

Source: Edge Health and Oxera.

3.2 Infectious days screened

For the full compliance framework, the percentage of infectious individuals screened and infectious days screened show similar trends.

In the full compliance framework, 58% of infectious days are screened out by on-arrival testing using RT-PCR technology and 48% of infectious days are screened out by on-arrival testing using RT-LAMP technology. RT-PCR screens a higher proportion of passengers as it is assumed to be more sensitive than RT-LAMP testing. Similar to the infectious travellers released above, for certain cohorts of passengers who have false negative results, additional quarantine requirements for RT-PCR testing while waiting for results will mean fewer infectious days released into the community compared to the RT-LAMP testing scenario where no waiting is required.

In the full compliance framework, longer quarantine periods are associated with more infectious days screened out. However, compared to the current policy of a mandatory 14-day quarantine on arrival, tests administered after three-, five- and seven-day delays are all highly effective. In the full compliance framework, using RT-PCR, a median of 91% (three-day), 96% (five-day) and 97% (seven-day) of infectious days are screened. Using RT-LAMP, a median of 85% (three-day), 92% (five-day) and 95% (seven-day) of infectious days are screened, respectively. The marginal benefit of the seven-day policy compared to the five-day policy is minimal, suggesting that the additional days of quarantine may not result in additional infectious days screened out.

Table 3.2 Infectious days screened via screening strategies (full compliance framework)

Group	Description	Percent of infectious days screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	98% (92%, 100%)	98% (92%, 100%)
Pre-departure	Test three days before departure	68% (50%, 83%)	69% (53%, 85%)
	Test on departure	46% (28%, 64%)	NA
On arrival	Test on arrival	48% (29%, 63%)	58% (39%, 73%)
Post-arrival	Test three days after arrival	85% (71%, 95%)	91% (80%, 99%)
	Test five days after arrival	92% (83%, 100%)	96% (89%, 100%)
	Test seven days after arrival	95% (87%, 100%)	97% (91%, 100%)

Note: Median values are presented, along with 90% confidence intervals.

Source: Edge Health and Oxera.

When we consider the outputs from the non-compliance framework, the effectiveness of the mandatory 14-day quarantine upon arrival scheme substantially decreases. We estimate that only 25% of infectious days are prevented from entering the community via the 14-day quarantine policy. All testing schemes considered have better performance than quarantine alone. Furthermore, the impact of more infected travellers becoming detectable while waiting more days for a test is often outweighed by the impact of non-compliant individuals spending more time in the community and potentially spreading the infection while waiting for a test to be administered and the results to be processed.

Considering the impact of non-compliance, on-arrival testing is almost twice as effective as the 14-day quarantine policy. The highest proportion of days screened is through testing three days after arrival. This appears to be the tipping point where the increased proportion of passengers that can be detected via testing still outweighs the impact of non-compliant infectious individuals spending time in the community while waiting for test results.

In the non-compliance framework, RT-LAMP testing becomes marginally more effective at screening infectious days than RT-PCR testing in some scenarios despite its lower sensitivity. This is due to a shorter delay between test administration and test results for this technology, resulting in higher compliance if travellers receive positive SARS-CoV-2 tests.

Table 3.3 Infectious days screened via screening strategies (non-compliance framework)

Group	Description	Percent of infectious days screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	25% (8%, 42%)	25% (8%, 42%)
Pre-departure	Test three days before departure	34% (17%, 51%)	36% (19%, 53%)
	Test on departure	47% (31%, 63%)	NA
On arrival	Test on arrival	51% (33%, 64%)	50% (34%, 64%)
Post-arrival	Test three days after arrival	60% (47%, 72%)	59% (46%, 70%)
	Test five days after arrival	53% (42%, 65%)	51% (39%, 64%)
	Test seven days after arrival	45% (32%, 57%)	43% (31%, 57%)

Note: Median values are presented, along with 90 percent confidence intervals.

Source: Edge Health and Oxera.

Our non-compliance scenario presented in Table 3.3 uses the conservative assumption that compliance with shorter quarantine requirements while waiting to be tested is equivalent to compliance with longer quarantine requirements. While there is currently no empirical evidence on differing compliance levels based on required quarantine duration, it stands to reason that individuals may have higher compliance rates when they need to quarantine for fewer days in the three- or five-day testing strategies compared to the 14-day quarantine strategy. Drawing on results from our sensitivity analysis (see A1 for all results), we can examine how testing strategy effectiveness changes with compliance.

For example, if pre-symptomatic and asymptomatic passengers complied with the shorter quarantine period of three or five days at a rate of 60%, 73% of infectious days would be prevented from entering the community by a three-day strategy and 71% of infectious days would be prevented from entering the community by a five-day strategy (see Table 3.).

If passengers complied with the shorter quarantine periods at a rate of 90%, 87% of infectious days would be prevented from entering the community by a three-day strategy and 90% of infectious days would be prevented from entering the community by a five-day strategy (see Table 3.). This suggests that testing scenarios with shorter quarantine requirements may be even more effective relative to the 14-day quarantine scenario compared to our conservative non-compliance framework where we assume that compliance is time-invariant.

In the pre-departure testing scenario with a test administered three days before departure, 60% compliance with the requirement to quarantine for three days between being tested and boarding a plane will result in 50% of infectious days being screened out, equivalent to the current 14-day quarantine policy.

Table 3.4 Infectious days screened via post-arrival screening strategies (60% compliance and 90% compliance sensitivity analysis)

		Percent of infectious days screened compared to syndromic screening on departure alone			
		60% compliance		90% compliance	
Group	**Description**	**RT-LAMP**	**RT-PCR**	**RT-LAMP**	**RT-PCR**
Pre-departure	Test three days before departure	48% (30%, 64%)	50% (32%, 67%)	62% (44%, 78%)	64% (47%, 80%)
Pre-departure	Test on departure	46% (30%, 63%)	NA	47% (30%, 66%)	NA
On arrival	Test on arrival	50% (35%, 64%)	54% (38%, 67%)	50% (34%, 64%)	57% (41%, 71%)
Post-arrival	Test three days after arrival	71% (58%, 82%)	73% (62%, 84%)	81% (67%, 92%)	87% (75%, 95%)
Post-arrival	Test five days after arrival	70% (57%, 81%)	71% (59%, 84%)	86% (76%, 95%)	90% (81%, 97%)
Post-arrival	Test seven days after arrival	66% (53%, 79%)	67% (54%, 80%)	87% (78%, 96%)	90% (81%, 98%)

Note: Median values are presented, along with 90 percent confidence intervals.

Source: Edge Health and Oxera.

4 Comparison with real-world evidence

The results from our previous report analysing real-world evidence on the effectiveness of traveller screening policies are summarised below.

Table 4.1 Summary of results from real-world evidence analysis

	Description of testing scheme	Proportion of infections identified through testing scheme
Jersey	Test on arrival for green (low-risk) countries[41]	54–63% on arrival
Toronto-Pearson Airport	Three tests: one at arrival, one after seven days of quarantine, and one after 14 days of quarantine	67–72% on arrival and 84–90% after seven days
Paris-CDG Airport	Two groups: one group with an on-arrival test only; one group with a pre-departure test and a second test after seven days of quarantine	76% on arrival and 90% after seven days
Iceland	Two tests: one on arrival; and one after five days of quarantine	64–69% on arrival and 83–90% after five days

Source: Edge Health and Oxera.

Along with demonstrating that on-arrival testing schemes identify much higher proportions of infectious travellers than previous figures reported by PHE, our analysis of real-world evidence showed that testing after five days identifies between 83% and 90% of potential infections, and testing after seven days shows nearly identical results of between 84% and 90%.[42] In our analysis of real-world evidence, the effectiveness of traveller screening schemes is defined as the proportion of all estimated incoming infections that are identified via each of the testing regimes.

To compare this analysis with our modelling results, we consider the proportion of modelled infectious travellers identified via the different screening schemes in relation to the incoming infectious travellers with syndromic screening alone (key scenarios selected from Table 3.1 are presented in Table 4.2 below).[43] This approach does not make assumptions about varying levels of compliance with quarantine requirements while waiting to be tested.

[41] We note that the Jersey testing scheme also includes testing on arrival for individuals travelling from amber and red countries, with five and 14 day quarantine periods respectively. However, we do not include the results for individuals travelling from these countries in our analysis due to data availability.
[42] See Oxera and Edge Health (2020), 'Review of case studies of effectiveness of testing schemes', 2 November, for full outline of calculations and assumptions.
[43] With a few caveats around the different calculation methods for the effectiveness of passenger screening regimes, our methodology compares the effectiveness to a baseline that includes compliance with quarantine measures should travellers become symptomatic, while the real-world evidence evaluates infected travellers identified via testing compared to the total incoming infected travellers (estimation of total incoming infected travellers varies based on data availability).

Table 4.2 Percentage of travellers identified via screening schemes (100% compliance)

Group	Description	Percent of infectious travellers screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
On arrival	Test on arrival	47% (31%, 60%)	58% (41%, 70%)
Post-arrival	Test five days after arrival	90% (81%, 98%)	94% (86%, 100%)
Post-arrival	Test seven days after arrival	93% (84%, 100%)	95% (87%, 100%)

Note: Median values are presented, along with 90% confidence intervals.

Source: Edge Health and Oxera.

Our estimates of the percentage of travellers screened via each of these schemes suggest that an RT-PCR test on arrival identified 58% of infectious travellers. This figure aligns to the range reported by the Jersey study and is in line with the lower end of the estimates from the Iceland study.

Although the five- and seven-day schemes considered in the analysis of real-world testing schemes are both dual-testing schemes, rather than the single-testing schemes considered in our modelling, we find that a similar proportion of travellers are identified through the seven-day testing scheme compared to the five-day testing scheme (94% vs 95% for RT-PCR testing and 90% vs 93% for RT-LAMP testing).

As real-world evidence on pre-departure schemes is not currently available, we were not able to benchmark our modelling results against real-world evidence. This gap warrants further investigation, for example by piloting this scheme for incoming UK passengers.

5 Conclusion

In line with the results from our analysis of real-world evidence, we find that a significantly higher proportion (58%) of infectious passengers are identified by on-arrival testing compared to the 7% figure estimated by PHE. In comparison to previous analyses by LSHTM and APHA, where the proportion of infectious travellers screened through on-arrival testing was estimated to be 45% and 40% respectively, our estimated effectiveness of on-arrival testing is also higher. However, our estimates do align with our analysis of real-world evidence on the effectiveness of on-arrival testing schemes.

In contrast to the original LSHTM study, we also find that there is only a marginal benefit of a seven-day quarantine period before testing compared to a five-day quarantine, in terms of infectious passengers screened, even when full compliance is assumed.[44] Again, this aligns with the results of our analysis of real-world evidence.

In our analysis of infectious days screened for the non-compliance framework, we find that the 14-day quarantine period requirements are significantly less effective at screening infectious days from the community than any of the testing regimes. We find that of the three-, five-, and seven- day testing schemes, the three-day scheme performs the best and the seven-day scheme has the lowest effectiveness. We also find that on arrival testing is twice as effective as the current quarantine policy.

Assuming that compliance with shorter quarantine periods is the same as for longer quarantine periods,[45] roughly 60% of infectious days would be screened through the three-day testing scenario in our central non-compliance framework. If, however, compliance with shorter quarantine periods is higher than longer quarantine periods, 73–87% (60–90% compliance) of infectious days could be screened through the three-day testing policy. If compliance with shorter quarantine periods were to improve similarly for the five-day testing scenario, 71–90% (60–90% compliance) of infectious days would be screened.

We also model the effectiveness of pre-departure schemes in this analysis, finding that testing three days prior to departure and testing on departure screen 36% and 47% of infectious days, respectively, in the non-compliance framework. However, we were not able to benchmark these results against real-world data due to a lack of evidence. Therefore, further pilot schemes testing the efficacy of these schemes in practice may be warranted.

In our analysis, we have focused on data from August 2020 given the recent announcements regarding national lockdowns in countries across Europe (including the UK). We consider that data from the summer months is also a better approximation of traveller volumes for future months where COVID-19 infection levels are sufficiently under control such that more international travel will be feasible.

Due to data constraints, we have not considered potential differences in COVID-19 infection levels in the passenger population based on demographic differences with the general population. If infection rates were corrected for demographics, we would expect passenger prevalence to be lower than that of the general population. We use the methodology from the LSHTM paper to

[44] This is also observed for infectious days for the full compliance scenario.
[45] As we do in our central non-compliance scenario where 28% of pre-symptomatic and asymptomatic passengers comply with quarantine requirements of varying lengths.

estimate prevalence, which does not account for differences in age/comorbidity structures when estimating prevalence from deaths data.

Importantly, the risk of introducing infections from international travel should be assessed relative to domestic infection levels. As an illustrative example, we consider the absolute numbers of infectious travellers attempting to travel per week and how many travellers are screened at each stage of the analysis.

For projected weekly incoming passenger volumes of 409,800 from the EU,[46] we estimate that 233 of them were infected prior to their flight. Of these 233 infected passengers from the EU, 89 passengers would be screened due to being symptomatic at the time of departure, leaving 144 infected passengers travelling. 42 of these passengers would quarantine upon arrival due to symptoms or would no longer be infectious at the time of arrival, leaving 102 infectious passengers potentially entering the community. Of these 102 passengers, 57 would be screened through on arrival testing, resulting in 45 infectious travellers being released into the UK population from the 409,800 intending to travel, or 0.01% of air travellers. This is equivalent to one infectious person per 10,000 travellers.

Over September and October, the ONS has estimated that there are 57 infections in England per 10,000 population. Given that a number of passengers travelling from the EU to the UK do not have to adhere to the quarantine policy due to travel corridors, and given there is no testing scheme in place, it is likely that a number of infectious travellers are being released into the community under the government's current policy.

Similarly, for the USA, based on incoming passenger volumes of 6,871 per week, we estimate that 33 individuals would have been infected prior to their flight. Of these 33 individuals, 12 would be screened due to being symptomatic at the time of departure, leaving 21 infected passengers travelling. Seven passengers would quarantine upon arrival due to symptoms or would no longer be infectious at time of arrival, leaving 14 infectious passengers potentially entering the community. Of these 14 passengers, eight would be screened through on arrival testing, resulting in six infectious travellers, or 0.09% of air passengers, being released. This is equivalent to nine infectious persons per 10,000 passengers. Over September and October, the ONS has estimated that there are 57 infections in England per 10,000 population.

While over the summer months infections in the UK/Europe were significantly lower than infection levels in the USA, given that the situation has worsened significantly in the UK/Europe, infections are as of November likely higher in the UK than in the USA. Tracking diverging patterns of infection levels in the coming months, particularly after the second national lockdown in the UK, will be important in determining the appropriate policy.

[46] Projections for potential air traffic volumes in coming months based on 2019 average monthly passenger volumes, scaled for August 2020 data.

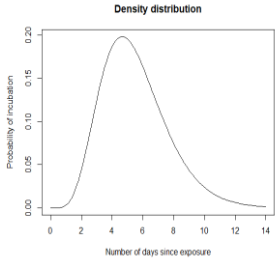
A1 Appendix

A1.1 Input values and sources

In the table below we set out the key assumptions used in this modelling work.

* Denotes no source.

Table A1.1 Key modelling assumptions

Model input		Description
Number of people intending to fly	Value	Monthly average historical volumes scaled by a factor of 0.24 for EU and s0.03 for the USA (reflecting reported traffic decrease in August 2019 versus August 2020)[47]
Departure countries	Value	EU and USA*
Duration of flight	Value	Two hours for EU flights and eight hours for USA flights*
Proportion of infected passengers (prevalence estimates)	Value	Based on prevalence of the departure country. Methodology from Russell et al. (2020) used to estimate under-ascertainment of SARS-CoV-2 cases in Europe and the USA. Figures updated to reflect data from August 2020 Underlying age/comorbidity structures and passenger demographics not considered[48]
Proportion of asymptomatic cases	Value	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)[49]
Incubation period (i.e. time from exposure to onset of symptom)	Value	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[50] 

[47] 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/

[48] 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

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Model input		Description
Infectious period	Value	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 95%: (1.2, 14.4) days[51]
Symptomatic period (i.e. time after onset of symptoms until no longer symptomatic)	Value	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[52]
RT-PCR sensitivity	Value	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[53]
RT-LAMP testing sensitivity	Value	A scaling factor for the relative effectiveness of RT-LAMP testing (.9) compared to RT-PCR testing is applied to the RT-PCR test sensitivity distribution[54]
Proportion stopped from flying through syndromic screening measures (symptomatic and asymptomatic)	Value	70% of travellers who were symptomatic at their intended departure time were either prevented from travelling or chose not to travel. 0% of asymptomatic infected travellers are stopped from boarding[55]
Compliance rate	Value	28% for asymptomatic or pre-symptomatic passengers, 71% for symptomatic passengers[56]

[51] 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

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A1.2 Full modelling results

Table A1.2 Infectious days screened compared to baseline (full compliance)

Group	Description	Percent of infectious days screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	98% (92%, 100%)	98% (92%, 100%)
Pre-departure	Test three days before departure	68% (50%, 83%)	69% (53%, 85%)
Pre-departure	Test on departure	46% (28%, 64%)	NA
On arrival	Test on arrival	48% (29%, 63%)	58% (39%, 73%)
Post-arrival	Test one day after arrival	63% (44%, 79%)	73% (54%, 87%)
Post-arrival	Test two days after arrival	76% (58%, 89%)	84% (69%, 95%)
Post-arrival	Test three days after arrival	85% (71%, 95%)	91% (80%, 99%)
Post-arrival	Test four days after arrival	90% (79%, 98%)	95% (86%, 100%)
Post-arrival	Test five days after arrival	92% (83%, 100%)	96% (89%, 100%)
Post-arrival	Test six days after arrival	94% (86%, 100%)	97% (90%, 100%)
Post-arrival	Test seven days after arrival	95% (87%, 100%)	97% (91%, 100%)
Post-arrival	Test eight days after arrival	96% (89%, 100%)	98% (91%, 100%)

Table A1.3 Infectious days (non-compliance scenario)

Group	Description	Percent of infectious days screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	25% (8%, 42%)	25% (8%, 42%)
Pre-departure	Test three days before departure	34% (17%, 51%)	36% (19%, 53%)
Pre-departure	Test on departure	47% (31%, 63%)	NA
On arrival	Test on arrival	51% (33%, 64%)	50% (34%, 64%)
Post-arrival	Test one day after arrival	56% (40%, 68%)	55% (40%, 67%)
Post-arrival	Test two days after arrival	59% (46%, 72%)	59% (44%, 70%)
Post-arrival	Test three days after arrival	60% (47%, 72%)	59% (46%, 70%)
Post-arrival	Test four days after arrival	57% (46%, 69%)	56% (44%, 68%)
Post-arrival	Test five days after arrival	53% (42%, 65%)	51% (39%, 64%)
Post-arrival	Test six days after arrival	49% (37%, 62%)	47% (35%, 60%)
Post-arrival	Test seven days after arrival	45% (32%, 57%)	43% (31%, 57%)
Post-arrival	Test eight days after arrival	41% (29%, 54%)	41% (28%, 54%)

Table A1.4 Infectious travellers (full compliance scenario)

Group	Description	Percent of infectious travellers screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	95% (88%, 100%)	95% (88%, 100%)
Pre-departure	Test three days before departure	67% (55%, 79%)	69% (57%, 81%)
Pre-departure	Test on departure	47% (32%, 60%)	NA
On arrival	Test on arrival	47% (31%, 60%)	58% (41%, 70%)
Post-arrival	Test one day after arrival	62% (46%, 75%)	72% (58%, 83%)
Post-arrival	Test two days after arrival	74% (61%, 85%)	83% (71%, 92%)
Post-arrival	Test three days after arrival	83% (71%, 92%)	89% (79%, 96%)
Post-arrival	Test four days after arrival	88% (77%, 96%)	93% (84%, 100%)
Post-arrival	Test five days after arrival	90% (81%, 98%)	94% (86%, 100%)
Post-arrival	Test six days after arrival	92% (83%, 100%)	95% (87%, 100%)
Post-arrival	Test seven days after arrival	93% (84%, 100%)	95% (87%, 100%)
Post-arrival	Test eight days after arrival	93% (86%, 100%)	95% (88%, 100%)

A1.3 Sensitivity analysis

Table A1.5 Infectious days screened—18% quarantine compliance

Group	Description	Percent of infectious days screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	16% (1%, 33%)	16% (1%, 33%)
Pre-departure	Test three days before departure	29% (14%, 45%)	32% (16%, 48%)
Pre-departure	Test on departure	47% (30%, 64%)	NA
On arrival	Test on arrival	50% (32%, 66%)	49% (33%, 63%)
Post-arrival	Test one day after arrival	55% (38%, 68%)	53% (36%, 65%)
Post-arrival	Test two days after arrival	57% (43%, 70%)	55% (41%, 67%)
Post-arrival	Test three days after arrival	57% (43%, 69%)	55% (41%, 66%)
Post-arrival	Test four days after arrival	53% (39%, 66%)	50% (37%, 63%)
Post-arrival	Test five days after arrival	48% (34%, 61%)	45% (31%, 59%)
Post-arrival	Test six days after arrival	43% (29%, 56%)	40% (26%, 54%)
Post-arrival	Test seven days after arrival	38% (24%, 53%)	36% (22%, 51%)
Post-arrival	Test eight days after arrival	34% (20%, 49%)	33% (19%, 48%)

Table A1.6 Infectious days screened—60% quarantine compliance

Group	Description	Percent of infectious days screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	53% (36%, 69%)	53% (36%, 69%)
Pre-departure	Test three days before departure	48% (30%, 64%)	50% (32%, 67%)
Pre-departure	Test on departure	46% (30%, 63%)	NA
On arrival	Test on arrival	50% (35%, 64%)	54% (38%, 67%)
Post-arrival	Test one day after arrival	60% (44%, 72%)	63% (47%, 75%)
Post-arrival	Test two days after arrival	67% (51%, 78%)	69% (56%, 80%)
Post-arrival	Test three days after arrival	71% (58%, 82%)	73% (62%, 84%)
Post-arrival	Test four days after arrival	71% (59%, 82%)	73% (61%, 83%)
Post-arrival	Test five days after arrival	70% (57%, 81%)	71% (59%, 84%)
Post-arrival	Test six days after arrival	68% (56%, 80%)	69% (56%, 82%)
Post-arrival	Test seven days after arrival	66% (53%, 79%)	67% (54%, 80%)
Post-arrival	Test eight days after arrival	65% (51%, 78%)	66% (51%, 79%)

Table A1.7 Infectious days screened—90% quarantine compliance

Group	Description	Percent of infectious days screened compared to syndromic screening on departure alone	
		RT-LAMP	RT-PCR
Current policy	Mandatory 14-day quarantine upon arrival	81% (64%, 92%)	81% (64%, 92%)
Pre-departure	Test three days before departure	62% (44%, 78%)	64% (47%, 80%)
Pre-departure	Test on departure	47% (30%, 66%)	NA
On arrival	Test on arrival	50% (34%, 64%)	57% (41%, 71%)
Post-arrival	Test one day after arrival	63% (45%, 77%)	70% (53%, 82%)
Post-arrival	Test two days after arrival	73% (57%, 85%)	80% (66%, 90%)
Post-arrival	Test three days after arrival	81% (67%, 92%)	87% (75%, 95%)
Post-arrival	Test four days after arrival	85% (73%, 94%)	89% (80%, 97%)
Post-arrival	Test five days after arrival	86% (76%, 95%)	90% (81%, 97%)
Post-arrival	Test six days after arrival	87% (77%, 96%)	90% (81%, 97%)
Post-arrival	Test seven days after arrival	87% (78%, 96%)	90% (81%, 98%)
Post-arrival	Test eight days after arrival	88% (77%, 96%)	90% (79%, 98%)

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