
Assessment of the effectiveness of rapid testing for SARS-CoV-2

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List of abbreviations

Abbreviation		Explanation
NAATs	Nucleic Acid Amplification Tests	Type of test that detects pathogen DNA or RNA in a sample. Examples of NAATs include PCR and LAMP tests.
RT-PCR	Reverse Transcription Polymerase Chain Reaction	Type of test to detect if a person is currently infected with SARS-CoV-2.
dPCR	Digital Polymerase Chain Reaction	Type of test to detect if a person is currently infected with SARS-CoV-2.
RT-LAMP	Reverse Transcriptase Loop-mediated Isothermal Amplification	Type of test to detect if a person is currently infected with SARS-CoV-2.
Ag-RDT	Antigen-detecting rapid diagnostic tests	Type of test to detect if a person is currently infected with SARS-CoV-2, also referred to as an antigen test.
CRISPR	Clustered regularly interspaced short palindromic repeats	A type of gene editing technology that has also been employed in a test to detect if a person is currently infected with SARS-CoV-2.

Executive summary

This study considers the effectiveness of the most widely used testing technologies. It shows that while PCR testing is the most precise technology for the detection of the SARS-CoV-2 virus (i.e. it has the highest sensitivity), there are a number of antigen tests that are effective at identifying the most infectious air passengers.

Antigen testing also has operational benefits. It does not require significant equipment or laboratory facilities to process results, and the test can be taken closer to the time of departure due to its rapid turnaround time. Lower prices also mean that antigen testing is less of an economic barrier to travel.

Over the last year, governments have taken the necessary measures to prevent the further spread of COVID-19 by placing significant constraints on international travel, including bans on entry by non-citizens, quarantine (at home or in hotels), and testing.

The roll-out of vaccination programmes at scale will be key to facilitating the reopening of international travel. However, it is likely that a proportion of the population will remain unvaccinated and that countries will move at different speeds on vaccination programmes. As a result, testing is likely to be a part of governments' strategies to reopen international borders, and at least some forms of testing may remain in place for international travel for some time.

At present, molecular tests, such as RT-PCR or RT-LAMP tests, are the most commonly used type of testing technology for international air travel, although antigen tests are increasingly being used across a number of jurisdictions. Molecular tests have high sensitivity, but take time to process and require significant infrastructure.

As mass vaccination builds confidence and passenger volumes start to return, the ability to test quickly and at scale with manageable costs is critical to the aviation sector's future. The recent experience in the UK is that antigen testing has been used for HGV drivers, teachers, schoolchildren, and university students. Still, there has been reluctance to introduce the technology to aviation, principally based on how effective antigen testing is for identifying and preventing people with COVID-19 from infecting others.

This report explores the effectiveness, and economic and operational elements, of antigen testing for international air travel compared to other forms of testing, such as PCR and LAMP. The key findings from this work are as follows.

- There are over a hundred different antigen tests available for COVID-19, but only a few tests are approved in multiple jurisdictions. Almost all achieve high specificity (i.e. people without COVID-19 are correctly identified with a negative test). However, there is a wide range of sensitivities (i.e. people with COVID-19 that are correctly identified with a positive test). The principal factor determining sensitivity appears to be the brand of the test, the population sample (e.g. symptomatic versus asymptomatic people), and the viral load of people tested (higher viral load tending to be correlated with better results).
 - A number of antigen tests have been proven to meet WHO/FDA standards in real-world settings and have comparable performance to PCR tests. The
-

EU has also published a list of recognised antigen tests that meet performance standards. Discrepancies between PCR and antigen testing can, among other factors, occur due to antigen tests being less sensitive at very early stages of infection and PCR tests picking up old infections (that are no longer transmissible).

- It is essential to understand how well a test identifies an infection and, consequently, screens out infectious days (i.e. the number of days when a person may be infectious). As part of this study, we have undertaken our own modelling of the effectiveness of different types of tests in detecting COVID-19 in air passengers, building on our previous work.¹ We find that high-performing antigen tests screen a comparable proportion of infectious days to PCR and LAMP tests. For example, when considering a test on arrival, a PCR test screens 72% of infectious days, compared to 65% for a LAMP test and 63% for an antigen test. The differences in performance between PCR, LAMP, and antigen tests narrow further with the introduction of a post-arrival quarantine period. A PCR test three days after arrival screens 79% of infectious days compared to 75% for antigen, and PCR and antigen tests both screen 74% of infectious days five days after arrival. Importantly, an antigen test administered on departure screens 62% of infectious days, a comparable proportion to a ten-day quarantine requirement (the current requirement in the UK) when quarantine compliance is taken into account.
- When high-performing antigen tests are used to screen international passengers, passengers arriving into the UK from either the US or EU present a lower infection risk relative to the domestic population. This is the case even when prevalence rates in the US/EU are highest relative to the UK, and only a single antigen test is administered before departure. For example, based on average passenger volumes between the USA and the UK in 2020, monthly air passengers not screened by an antigen test accounted for 0.008% of total infectious days in the UK. This amounts to eight infectious days per 100,000 in the community. Even if air passenger volumes from the USA recovered to 30% of 2019 volumes, air passenger infectious days would be 0.085% of total infectious days in the community—i.e. only eight infectious days per 10,000. When domestic prevalence rates are already high or the population is vaccinated, the relative risk of air passengers spreading infection may even be lower.
- Finally, antigen tests are significantly cheaper than PCR tests. In some countries, PCR tests are at least three to four times more expensive than antigen tests. Many governments require several tests for international travel, which further increase the financial burden for passengers. A higher cost of travelling is likely to lead to lower passenger volumes. Based on a high-level analysis of five example routes, and incorporating current testing requirements, passenger volumes could decline by 65% when PCR tests are required or 30% when antigen testing is used. This would have a significant effect on the aviation sector, government tax revenue, and other sectors of the economy.

¹ Oxera and Edge Health (2020), 'Modelling the effectiveness of airport testing regimes', November.

1 Introduction

Oxera and Edge Health have been commissioned by the International Air Transport Association ('IATA') to undertake a review of evidence on testing technologies for SARS-CoV-2, and to specifically consider their use in the context of air passenger testing.

There are a number of different testing regimes in place for international travellers across jurisdictions. Many countries (e.g. the USA) require a pre-departure test taken 72 hours before boarding in order to be permitted entry. Other countries require tests on arrival, for all travellers or individuals arriving from certain countries, either at the airport or a certain number of days after arrival. Some countries, such as the UK and Canada, require both pre-departure tests and multiple on-arrival tests, in addition to mandatory quarantine. Testing is therefore already an important part of air travel.

There are currently three main types of tests for SARS-CoV-2: molecular, antigen, and antibody tests. Molecular (e.g. RT-PCR and RT-LAMP) and antigen tests are both diagnostic tests that detect active infections, while antibody tests detect past infections. The focus of this study is on the most commonly available diagnostic tests: molecular and antigen tests.

There is a great deal of literature on these different types of tests, including empirical studies on their effectiveness, and papers setting out their advantages and disadvantages. There is also an increasing amount of real-world data from instances in which these tests have been used on different populations (e.g. students, air passengers, etc.). We have systematically reviewed papers focusing on real-world evidence of test performance (rather than theoretical modelling).

An understanding of the effectiveness and economics of different testing technologies is important in determining which type of screening procedure is best suited to help safely and effectively reopen international travel. In particular, an improved understanding of rapid testing is key to evaluating the appropriate testing scheme that minimises the risk to public health while best enabling international travel to safely restart, and which can accommodate a rise in passenger numbers over time (e.g. with an increase in vaccination rates across countries).

This report is structured as follows.

- Section 2 sets out an overview of the current testing technologies for COVID-19.
- Section 3 provides a comparison of different testing technologies across a number of dimensions in the context of their use for air passengers.
- Section 4 includes our own analysis of the effectiveness of different types of tests for air passengers.
- Section 5 sets out a high-level analysis of the potential impact that the additional cost of different types of tests may have on air travel.
- Section 6 concludes with a discussion of the implications for future policy with respect to air travel.

The appendices include the detailed results of our literature review and analysis.

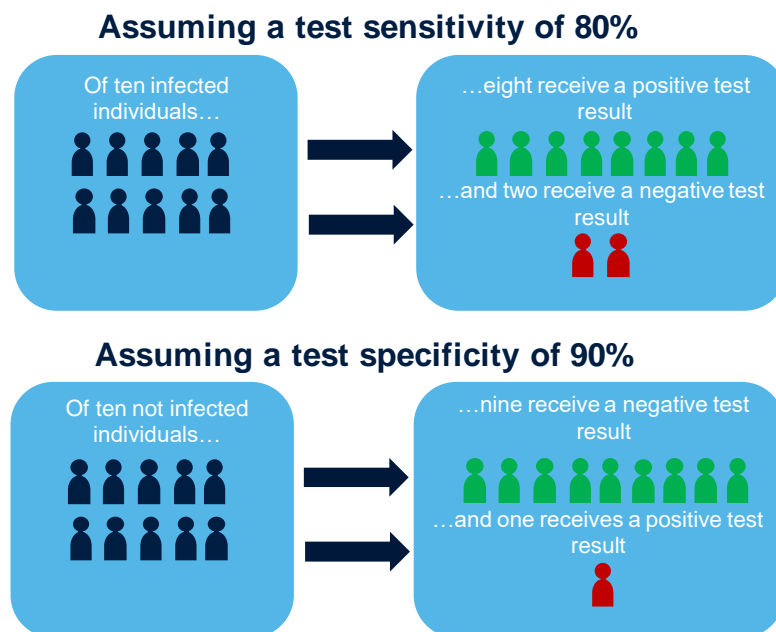
2 Overview of testing technologies for SARS-CoV-2

2.1 How is the effectiveness of testing technologies measured?

Testing technologies are evaluated based on their ability to correctly identify whether an individual currently has, or has had, the condition that is being tested for—in this case an infection with the SARS-CoV-2 virus.² The effectiveness of such tests (also called ‘assays’ in this context) is generally measured according to **sensitivity** and **specificity**.

- **Sensitivity** measures the share of virus carriers that are correctly identified with a test. For example, a 100% sensitivity implies that there are no false negatives—i.e. everybody who is actually a carrier of the virus receives a positive test result—while an 80% sensitivity implies that of 100 individuals that are infected with coronavirus, 80 receive a positive test result and 20 receive a negative test result.
- **Specificity** measures the share of non-virus carriers that are correctly identified with a test. A 100% specificity implies that there are no false positives—i.e. nobody who does not have the virus receives a positive test result—while a 90% sensitivity implies that of a population of 100 individuals who are not infected with the coronavirus, 90 receive a negative test result and ten receive a positive test result.

Figure 2.1 Sensitivity and specificity explained



Source: Oxera and Edge Health.

The World Health Organisation (‘WHO’) recommends that coronavirus tests should have a minimum performance standard in order to be employed as a testing method. It recommends that diagnostic tests (e.g. molecular tests—see section 2.2 below) should satisfy minimum performance requirements of $\geq 80\%$ sensitivity and $\geq 97\%$ specificity compared to a reference PCR test, based on well-designed and executed evaluations in representative populations.³ This is

² SARS-CoV-2, or the severe acute respiratory syndrome coronavirus 2, is the virus that causes the coronavirus disease, or COVID-19.

³ WHO (2020), ‘Antigen-detection in the diagnosis of SARS-CoV-2 infection using rapid immunoassays: Interim guidance’, 11 September. The accuracy of tests in the real world, referred to as ‘diagnostic’ or

the same as the UK government's requirements for pre-departure tests,⁴ though tests taken as part of the test to release scheme need to have a sensitivity and specificity of at least 95%.⁵

A third relevant metric in this context is the **limit of detection**—i.e. the minimum amount of viral genome in a specimen that a test can detect. The quantity of virus in a given volume of fluid is sometimes also referred to as the 'viral load'. Sample populations with higher viral loads will lead to higher reported test sensitivity. For example, studies on SARS-CoV-2 viral shedding dynamics suggest that asymptomatic individuals demonstrate faster viral clearance than symptomatic individuals.⁶ Other studies of hospitalised patients indicate that higher viral load is correlated with greater disease severity.⁷

More broadly, the ability of testing to capture true infections is dependent on a range of factors, such as the stage of infection, the testing technology itself, how the test is set up and performed (including by who and under what conditions), and the potential for samples to be damaged or contaminated. More detail on what may cause false negatives or false positives is included in Box 2.1.

Box 2.1 What causes false negatives and false positives?

False negatives

- **Poor sampling technique.** Nasopharyngeal sampling is invasive and can feel unpleasant. When performed unsupervised, it might be carried out less thoroughly. Therefore, it may be less effective when administered by oneself, so the false negative rate may increase as sampling at home becomes more common.
- **Sample degradation.** Samples may degrade when stored or while being transported. This is more relevant for tests that need to be processed in a laboratory setting, such as the RT-PCR test.
- **Sampling too early or too late.** Viral shedding from individuals peaks just before, or at the onset of symptoms. If samples are taken early in infection (1–4 days after infection) or very late in an infection (8–12 days after symptoms have peaked), they have an increased false negative rate because viral loads are not high enough for a test to detect viral gene material.

False positives

- **Cross-reactions with other genetic material.** Other sources of DNA or RNA may have cross-reactive genetic material that can be picked up by a test.

'operational' performance, might also differ substantially from the analytical sensitivity and specificity measured in the laboratory setting.

⁴ The test must meet performance standards of $\geq 97\%$ specificity, $\geq 80\%$ sensitivity at viral loads above 100,000 copies/ml. Additional requirements can be found here: <https://www.gov.uk/guidance/coronavirus-covid-19-testing-for-people-travelling-to-england> (last accessed 17 March 2021).

⁵ These also need to be molecular tests and have limit of detection less or equal to 1,000 SARS-CoV-2 copies per millilitre. Additional requirements can be found here—see: <https://www.gov.uk/government/publications/testing-to-release-for-international-travel-minimum-standards-for-testing/minimum-standards-for-private-sector-providers-of-covid-19-testing-for-testing-to-release-for-international-travel> (last accessed 17 March 2021).

⁶ Cevik M. et al. (2020) 'SARS-CoV-2, SARS-CoV, and MERS-CoV viral load dynamics, duration of viral shedding, and infectiousness: a systematic review and meta-analysis', *The Lancet*, Vol2 Issue 1 E13-E22.

⁷ Fajnzylber, J. et al. (2020), 'SARS-CoV-2 viral load is associated with increased disease severity and mortality', *Nature Communication*, 11:5493, available from: <https://www.nature.com/articles/s41467-020-19057-5>.

- **Contamination during sampling or swab extraction.** This may happen if the swab head accidentally contacts, or is placed on, a contaminated surface (e.g. latex gloves, hospital surface).
- **Contamination of PCR laboratory consumables.** Contamination can spread between labs by transfer of equipment, chemicals, people or aerosol. Even experienced national labs can be affected. In early March 2020, coronavirus RT-PCR assays produced by the CDC were withdrawn after many showed false positives due to contaminated reagents.

Source: Mayers, C. and Baker, K. (2020), 'Impact of false-positives and false-negatives in the UK's COVID-19 RT-PCR testing programme', 3 June, available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/895843/S0519_Impact_of_false_positives_and_negatives.pdf (last accessed 17 March 2021).

Given the appearance of 'Variants of Concern' of the virus in the past few months—in particular the UK variant (B.1.1.7), the South African variant (B.1.351) and the Brazilian variant (P.1)—a fourth important measure of test quality is the **ability to detect variants**. While the evidence on variants is still developing, we discuss this further in section 3.5.

It is also important to consider the longer-term role that testing is likely to play in different settings—for example, in air travel—when making an assessment of the overall usefulness of a testing regime. In particular, as highlighted in a recent paper in the *New England Journal of Medicine*,⁸ the efficacy of a test must be considered in the context of:

- when in the course of an infection it works (see section 3.3);
- how often it can be used, i.e. how available and expensive it is (see section 3.4);
- whether its results are returned in time to prevent spread, i.e. how fast it can return results (see Table 2.3). This is particularly important in light of questions regarding individuals' compliance with quarantine (see section 4).

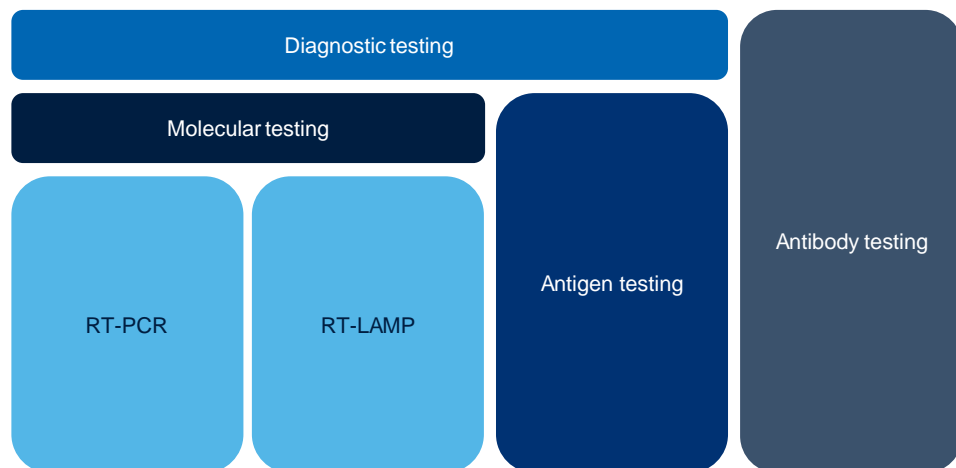
Additionally, for air travel, it is important to consider the ability to affordably scale testing to reasonable levels of passenger traffic (see section 5), and for it to be integrated into the passenger's journey efficiently. Therefore, it is important to consider a broader concept of effectiveness of testing than just sensitivity and specificity.

2.2 What are the types of tests for coronavirus?

The wide range of coronavirus tests can broadly be divided into **diagnostic tests** and **antibody tests**. The former diagnose a current infection, while the latter is used to test for a past infection. This is set out in Figure 2.2 below.

⁸ Mina J. M. et al. (2020), 'Rethinking Covid-19 Test Sensitivity — A Strategy for Containment', *The New England Journal of Medicine*, available at: <https://www.nejm.org/doi/full/10.1056/NEJMp2025631> (last accessed 24 March 2021).

Figure 2.2 Main testing technologies for SARS-CoV-2



Source: Oxera and Edge Health based on FDA.

Diagnostic tests can be further split into molecular tests and antigen tests. Molecular tests, which are based on the detection of SARS-CoV-2 RNA, are the most commonly used tests for the diagnosis of COVID-19.⁹ Antigen tests use lateral flow immunoassays,¹⁰ and are frequently referred to as lateral flow tests.¹¹

Antibody tests describe a variety of different types of tests that can determine if an individual has previously been exposed to COVID-19.¹² Recent academic literature shows that the accuracy of antibody tests is relatively high once a certain amount of time since infection has passed. A study by Rudolf et al. (2020)¹³ shows that the specificity of ten different antibody tests range between 91.5% and 100.0%.¹⁴

COVID-19 antibodies are likely to provide some protection against reinfection, but there is no consensus on the extent or duration of protection.¹⁵ If a more definitive link between antibodies and immunity is established, proof of antibodies could potentially serve as an alternative to a negative coronavirus test result (or a vaccine) for travelling or ending quarantine requirements in the future. However, for the purposes of this report, we focus on the role of

⁹ All of these assays are based on amplifying the viral RNA to detect the presence of the RNA. Different chemistries and methods are applied for amplifying the viral RNA to a detectable level. LabMedicineBlog (2020), 'COVID-19 Testing Explained', 2 June. For more details see: <https://labmedicineblog.com/2020/06/02/covid-19-testing-explained/> (last accessed 17 March 2021).

¹⁰ For immunoassays using colour labels, the coloured test line (indicating a positive test) results from the reaction of the SARS-CoV-2 antigen with SARS-CoV-2 antibodies (conjugated with colour particles). In sandwich assays, this complex then reacts with a second set of antibodies present on the test line, resulting in the accumulation of colour along the test line.

¹¹ Most antigen tests use a lateral flow test format and are therefore sometimes referred to as lateral flow tests. However, the lateral flow test format is commonly employed for HIV, malaria and influenza testing (as well as in pregnancy tests). Moreover, some of the antibody tests are also conducted using the lateral flow test format.

¹² The assays range from lateral flow cassettes to high throughput chemiluminescent based assays.

¹³ See: <https://www.medrxiv.org/content/10.1101/2020.08.18.20177204v3.full.pdf> (last accessed 24 March 2021).

¹⁴ Sensitivities for these tests range from 56.4% to 97% when testing for igG antibodies more than 21 days post symptoms, and from 25.1% to 91.9% when testing for igM antibodies seven to 28 days post symptoms. Combining tests that perform well for igG and igM antibodies further increases the accuracy to above 99%.

¹⁵ WHO (2020), 'Coronavirus disease (COVID-19): Serology, antibodies and immunity', 31 December, available at: <https://www.who.int/news-room/q-a-detail/coronavirus-disease-covid-19-serology#:~:text=There%20are%20many%20studies%20underway,these%20antibodies%20can%20vary> (last accessed 17 March 2021).

molecular and antigen testing. The following sections describe these tests in greater detail.

2.2.1 Molecular testing: RT-PCR and RT-LAMP

RT-PCR has high specificity and sensitivity; it is often considered the most reliable in COVID-19 diagnosis.¹⁶ Public Health England ('PHE'), an executive agency of the UK Department of Health and Social Care, has verified that RT-PCR tests show over 95% sensitivity and specificity in a laboratory setting.¹⁷ Preliminary estimates of the current rate of operational false-positive PCR tests in the UK are between 0.8% and 4.0%.¹⁸ The performance of RT-PCR tests tend to be consistent across brands. As a result, the sensitivity and specificity of other types of tests are often compared to PCR tests.

While PCR tests are the most precise diagnostic test for coronavirus, they have three main disadvantages.

- PCR tests are expensive—e.g. between £75 and £200 in the UK, between €70 and €140 in Germany, between €54 and €70 in France, between €90 and €100 in Spain, and between €60 and €80 in Italy.¹⁹ Therefore, requiring travellers to get a PCR test might have a significant impact on the affordability of air travel. Section 5 examines the cost of additional testing in greater detail.
- It needs to be processed in a laboratory setting. Although PCR testing capacities have been significantly expanded over the course of 2020, they may not be sufficient for processing (for instance) tests for a significant share of the travelling population, particularly in addition to the non-travelling population that may need such tests (see section 3.4).
- Given that PCR tests need to be processed in a laboratory setting, it takes time for individuals to receive their results. This makes the PCR test unsuitable for on departure/at arrival testing at airports and means that individuals may infect others in the time period while waiting for their test results if they are not required to (or do not comply with) quarantine. As an example, Figure 2.3 shows the average time elapsed between taking a PCR test and receiving the results at different test locations in the UK. Although the average number of hours has decreased from 42 in mid-December, the data shows that in January 2021 the median time taken to receive a PCR test result at local test centres in England was around 25 hours.

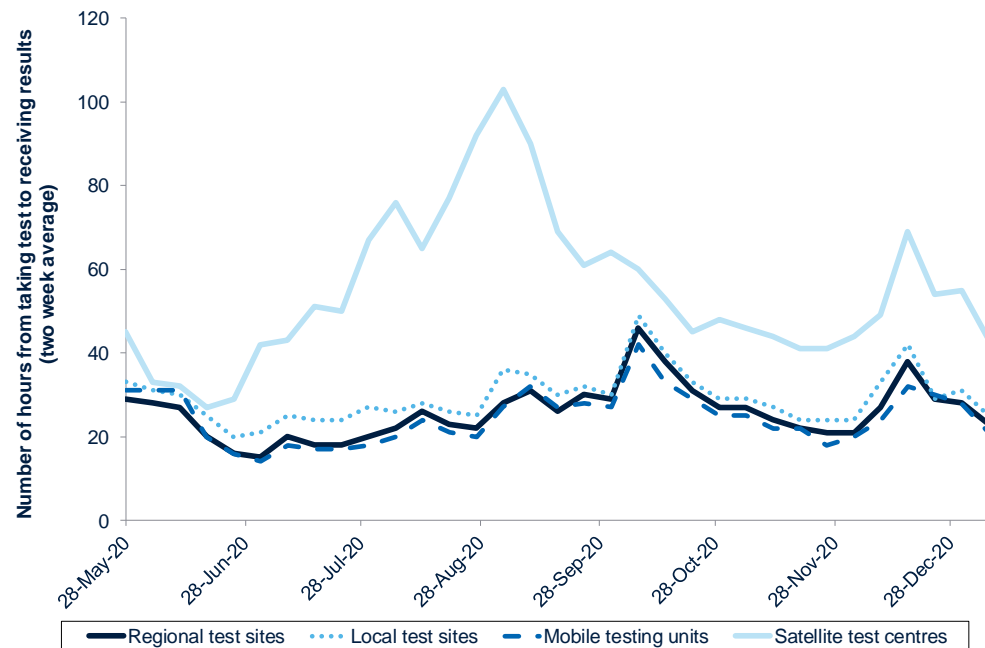
¹⁶ Xu, M., et al. (2020), 'COVID-19 diagnostic testing: Technology perspective', *Clinical and translational medicine*, **10**:4.

¹⁷ UK Government (2020), 'Impact of false-positives and false-negatives in the UK's COVID-19 RT-PCR testing programme', June.

¹⁸ Surkova, E. et al. (2020), 'False-positive COVID-19 results: hidden problems and costs', *The Lancet*, **8**:12, pp. 1167–8.

¹⁹ Coffey, H. (2021), 'Where to find cheap Covid-19 PCR tests for travel', *The Independent*, 1 December; and Kreder C. (2020), 'So teuer sind private Corona-Tests in anderen Ländern', *Capital*, 11 December.

Figure 2.3 Median time from testing to receiving results at different test locations, May 2020 to January 2021



Source: Oxera and Edge Health based on test and trace data from NHS.

Note: The values represent two week averages, i.e. the data point at 28 May 2020 refers to the average number of hours an individual in England had to wait from testing to receive the results between 28 May 2020 and 3 June 2020. The data presented here refers to 'pillar two' individuals, which is the wider population.

The impact of these disadvantages in terms of the potential use of PCR testing in the travel setting is discussed in greater detail in section 3.4.

In comparison to RT-PCR tests, LAMP tests require incubation at a constant temperature, thus eliminating the need for sophisticated instrumentation. This means that LAMP tests can be performed on-site and do not need to be transported to a laboratory. It therefore has several advantages: it can provide results in under 20 minutes, and can be evaluated without any equipment. However, these tests have a lower sensitivity than PCR tests. Sensitivity ranges from 70% to 95%, depending on the sample used (swab or saliva), test brand and whether RNA is extracted.²⁰ The specificity of LAMP tests has been found to be high across the board, with values ranging between 99% and 100%.²¹

The sensitivity of LAMP assays improves in samples with a higher viral load: a study from August 2020 shows that sensitivity ranges from 86% to 97.5% in samples with Ct values²² below 30.²³ LAMP tests therefore reliably detect

²⁰ Sensitivity was reported to be 70% for the OptiGene direct RT-LAMP test (no viral RNA extracted) on swabs, while sensitivity was reported to be 95% for the OptiGene RNA RT-LAMP test (with viral load extraction) on swabs.

²¹ UK Government (2020), 'Clinical evaluation confirms accuracy of LAMP test', 1 December, available at: <https://www.gov.uk/government/news/clinical-evaluation-confirms-accuracy-of-lamp-test> (accessed 17 March 2021) and Dao Thi, V. L. (2020), 'A colorimetric RT-LAMP assay and LAMP-sequencing for detecting SARS-CoV-2 RNA in clinical samples', *Science Translational Medicine*, 12:556.

²² The Ct (cycle threshold) value represents number of cycles of amplification required to produce a detectable amount of RNA – the cycle threshold is inversely correlated with the viral load. Low Ct values are associated with high viral loads. See also: University of Liverpool (2020), 'Liverpool Covid-19 Community Testing Pilot – Interim Evaluation Report', 23 December.

²³ Dao Thi, V. L. et al. (2020), 'A colorimetric RT-LAMP assay and LAMP-sequencing for detecting SARS-CoV-2 RNA in clinical samples', *Science Translational Medicine*, 12:556.

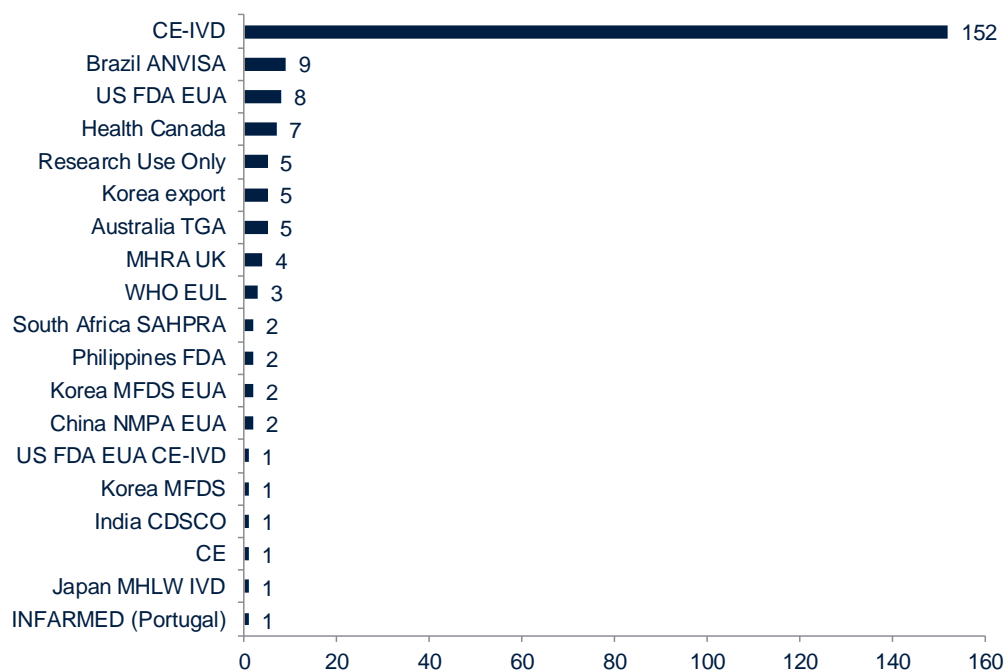
COVID-19 cases with high viral loads.²⁴ Prices for RT-LAMP tests are slightly lower than RT-PCR tests, for example currently averaging around £79 in the UK and €89 in Austria.²⁵

2.2.2 Antigen testing

The main advantage of an antigen test is its speed: it can deliver results within 20 minutes. As it does not require any laboratory equipment to process, it is easy to administer and can be employed on-site without much investment in facilities.

According to the Foundation for Innovative New Diagnostics (FIND), as of 17 March 2021, there were 165 commercialised antigen tests available—see Figure 2.4. Most of them have been approved for use in the EU according to CE-IVD, the relevant EU regulation.

Figure 2.4 Number of antigen tests approved by different regulatory authorities, as of March 2021



Source: Oxera and Edge Health, based on FIND data.

Note: 'EUA' stands for 'emergency use approval', 'EUL' stands for 'emergency use listing'. Oxera and Edge Health cannot ensure that the count above is complete because this data has been submitted voluntarily by test suppliers and is not independently verified by FIND.

On 17 February 2021, the European Union published a list of COVID-19 rapid antigen tests with test results that are mutually recognised by the EU Member States. The tests included in that list must fulfil the following criteria:

- carry CE-IVD marking;
- meet the minimum performance requirements of $\geq 90\%$ sensitivity and $\geq 97\%$ specificity;

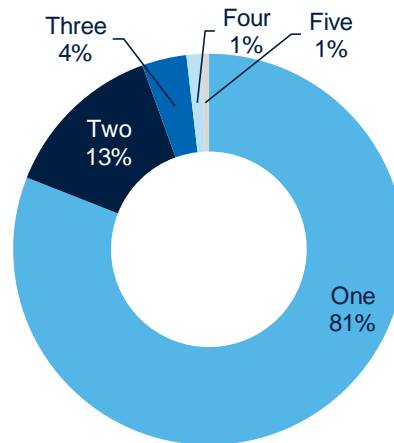
²⁴ Crozier, A. F. (2020), 'Rapid Response: Direct RT-LAMP for Hospital Screening', 9 November.

²⁵ Prices refer to LAMP tests offered by Collinson in the UK and FasTest in Austria. For more information, see <https://www.collinsongroup.com/en/covid-19-testing/test-information> and https://www.ots.at/presseaussendung/OTS_20210115_OTS0045/fastest-corona-test-center-neue-location-in-kaerntnerstrasse-erstmal-schnell-pcr-test (last accessed 25 March 2021).

- have been validated by at least one Member State as being appropriate for use in the context of COVID-19.²⁶

As set out in Figure 2.5, 81% of antigen tests have been approved by just one regulatory process, and only a handful of antigen tests have been approved by more than one authority. In particular, six tests have received approval by three or more regulatory regimes.

Figure 2.5 Number of regulatory authorities that have granted approval for a given antigen test, as of March 2021



Source: Oxera and Edge Health based on FIND data.

The six antigen tests that have received regulatory approval by three, four or five authorities are set out in Table 2.1 below. For each test we set out the name, manufacturer and the relevant approvals. Four of these tests are included in the approved list published by the European Union.²⁷ Of the six antigen tests that have secured approval by three or more regimes, only the Panbio™ COVID-19 Ag Rapid Test Device and STANDARD Q COVID-19 Ag Test have been certified by the WHO, and therefore comply with the WHO minimum performance requirements (at least in a laboratory setting) with certainty. Although the other tests have not been officially approved by the WHO, all of them provide clinical sensitivities and specificities above the WHO threshold of 80% and 97%.

²⁶ For each test, the following information must be provided: details on the methodology and results of studies, such as the sample type used for validation, the setting in which the use of the test was assessed, and whether any difficulties occurred as regards the required sensitivity criteria or other performance elements.

²⁷ The EU list also includes other highly effective tests that are not included in Table 2.1 such as the Siemens Healthineers, CLINITEST Rapid COVID-19 Antigen Test with a clinical sensitivity of 99.2% and a clinical specificity of 96.7% or the LumiraDX UK LTd, LumiraDx SARS-CoV-2 Ag Test with a clinical sensitivity of 97.6% and a clinical specificity of 96.6%.

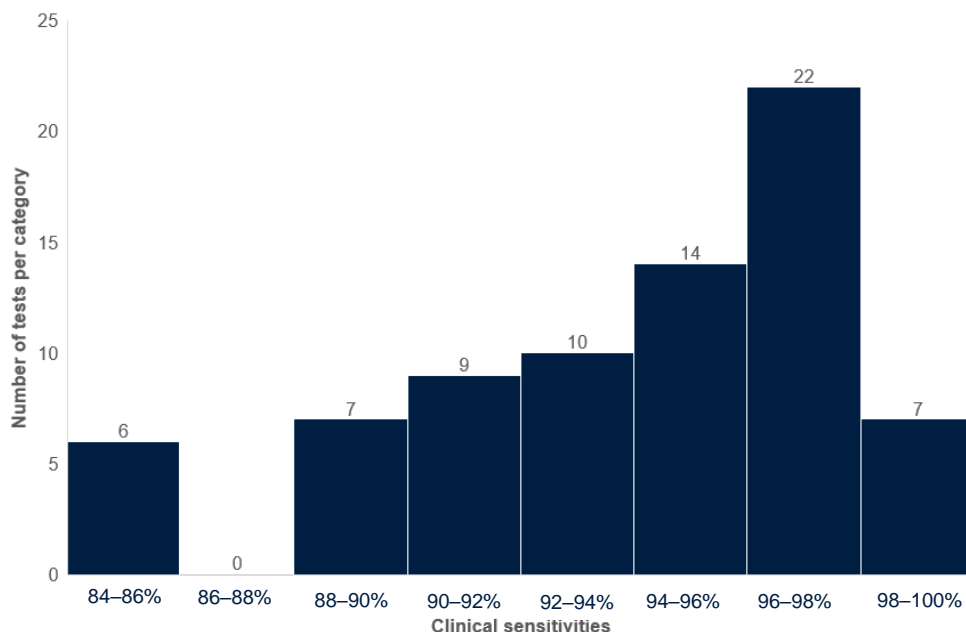
Table 2.1 Antigen tests that have been approved by more than two regulatory procedures, as of March 2021

Manufacturer name	Test name	Approving regulatory regimes	On common EU list	Clinical sensitivity (%)	Clinical specificity (%)
Abbott Diagnostics	Panbio™ COVID-19 Ag Rapid Test Device	Australia TGA; South Africa SAHPRA; WHO EUL	Yes	91.4	99.8
Becton Dickinson & Company	BD Veritor System for Rapid Detection of SARS-CoV-2	Australia TGA; Health Canada; US FDA EUA; CE-IVD	Yes	84	100
BIOHIT HealthCare (Hefei) Co., Ltd	SARS-CoV-2 Antigen quantitative assay kit (Enzyme-linked immunoassay)	Australia TGA; Brazil ANVISA; CE-IVD	No	91.2	100
Bionote Inc.	NowCheck COVID-19 Ag Test	Australia TGA; CE-IVD; Korea export	Yes	89.2	97.3
SD BIOSENSOR, Inc.	STANDARD Q COVID-19 Ag Test	South Africa SAHPRA; Brazil ANVISA; CE-IVD; WHO EUL; India CDSCO	Yes	91.4	99.8
Spring Healthcare Services AG	SARS-Cov-2 Antigen Rapid Test Cassette (Swab)	US FDA EUA; Brazil ANVISA; CE-IVD	No	84	100

Source: Oxera and Edge Health based on FIND data.

In fact, all of the tests included in the FIND database have clinical sensitivity values that are above the WHO threshold of 80%. Figure 2.6 shows the distribution of antigen tests according to their clinical specificities as reported by FIND. Seven tests report a clinical sensitivity above 98% and another 22 tests report a clinical sensitivity above 96%. This demonstrates that some antigen tests have very high sensitivities and are therefore able to correctly identify coronavirus infections, at least in a laboratory setting.

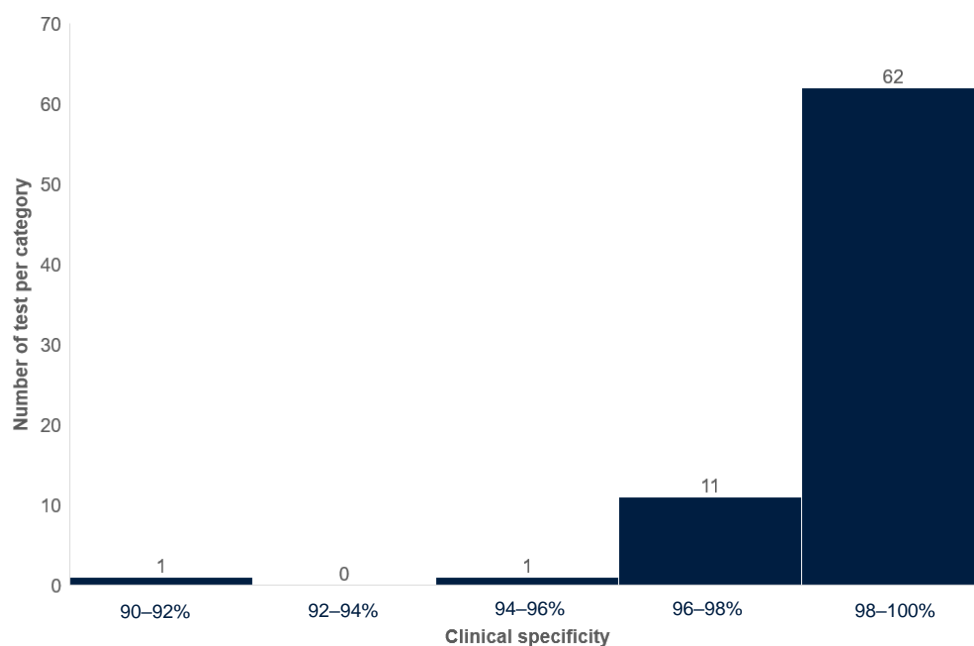
Figure 2.6 Clinical sensitivities of antigen tests included in FIND database, as of March 2021



Source: Oxera and Edge Health based on FIND data.

Most of the antigen tests in the FIND database also provide clinical specificity values above the WHO threshold of 97%. Figure 2.7 shows the distribution of antigen tests according to their clinical specificities. 62 tests report a clinical specificity above 98% and another 11 tests report a clinical specificity above 96% (at least in a laboratory setting). This illustrates that most antigen tests will provide low numbers of false positives and are therefore good at correctly identifying who is *not* infected with coronavirus.

Figure 2.7 Clinical specificities of antigen tests included in FIND database, as of March 2021



Source: Oxera and Edge Health based on FIND data.

The performance of antigen tests has been widely analysed in empirical studies and academic literature. Interestingly, the tests set out in Table 2.1 above are not the ones most widely studied in the academic literature. Our literature review has instead revealed a different set of tests that have been examined in medical trials.

Table 2.2 below sets out an overview of scientific studies that evaluate the real-world accuracy of antigen tests in relation to RT-PCR tests. A more detailed overview of academic studies is included in Appendix A1.

Table 2.2 Overview of academic studies that report real world efficacy of antigen tests

Name of test	Approved ²⁸	Sensitivity (%)	Specificity (%)
BinaxNOW	US FDA EUA	89	99.9
Bioeasy	CE-IVD	67–99	93–100
Coris	CE-IVD	30–58	96–100
Espline	-	81	100
Innova lateral flow (Liverpool study)	-	49	100
Panbio Abbott	WHO EUL, Australia, South Africa	66–74	100
RapiGEN	CE-IVD, Brazil and Philippines	28–62	100
SD Biosensor	WHO EUL, CE-IVD, Brazil and South Africa	62–77	99
Sofia antigen	US FDA EUA	41–80	98–99
Various (meta study)	-	0–94; mean of 56	100

Note: 'EUA' stands for 'emergency use approval'. For a full overview of the academic studies reviewed, as well as full list of sources, see Table A1.1 in Appendix A1.

Source: Analysis by Oxera and Edge Health.

While the specificity of antigen tests is reported to be high across all studies, sensitivities vary greatly from 30% to 99%. A meta study conducted by Dinnes et al. (2020),²⁹ based on five studies and 943 samples, reports sensitivities ranging from 0% to 94% with a mean sensitivity of 56%.

A closer look at these studies reveal a number of important takeaways.

- **Some tests perform better than others.** While some tests such as Coris or RapiGen perform poorly to moderately across a number of studies, recent studies show high accuracy for Bioeasy and BinaxNOW in particular. The BinaxNOW antigen test, for instance, has been shown to have a sensitivity of 89% and specificity of 99.9% when tested on a population of asymptomatic and symptomatic people, which could be considered representative of the travelling population.
- **Antigen tests perform better on symptomatic people compared to asymptomatic people.** Across all studies reviewed, antigen tests show higher sensitivity for symptomatic individuals. The sensitivity of the Sofia

²⁸ Based on FIND data. Oxera and Edge Health cannot ensure that this data is complete because this data has been submitted voluntarily by test suppliers and is not independently verified by FIND.

²⁹ Dinnes, J. et al. (2020), 'Rapid, point-of-care antigen and molecular-based tests for diagnosis of SARS-CoV-2 infection', *The Cochrane database of systematic reviews*, 8.

antigen test, for instance, is 80% on symptomatic people, but reduces to 42% when used on an asymptomatic population.

- **Antigen tests seem to perform better on patients with high viral loads.** Even the less accurate tests, such as Innova or RapiGen, report better performance on individuals with high viral loads. The Innova test shows a sensitivity of 66.7% for patients with a Ct value³⁰ of under 25, while the RapiGen test produces a sensitivity of 84.9% on high viral load patients.

We note that there are no clear trends identified in terms of newer developed tests performing better. However, it is often difficult to determine when the tests were developed and commercialised, and it is therefore difficult to determine if tests have been improving over time.

It is less clear from these studies whether the person administering the test has an impact on test efficacy. It has been suspected that one of the reasons why a real-world trial at the University of Birmingham, where 7,000 symptom-free students took a self-administered Innova rapid antigen test, performed so poorly might have been that students were not able to correctly extract their swab samples. As a result, there were insufficient amounts of the virus protein for the antigen test.³¹

However, a study conducted at Charité hospital in Berlin during November and December 2020 found that study participants were able to reliably perform the rapid antigen tests themselves. Although professional testing had a slightly higher sensitivity (85.0%) than self-administered tests (82.5%), this difference was small. Furthermore, it disappeared altogether when only considering samples with a high viral load, where both professionally and self-administered antigen tests had sensitivity values of 96.6%.³²

A recent *Nature* article suggests that differences in how laboratories translate Ct values into viral loads might have been driving the poor results of the Liverpool mass testing with the Innova antigen test.³³ The public health and informatics researcher Iain Buchan at the University of Liverpool, who led the trial, stated that at the laboratory that processed the samples, Ct values of 25 equated to much lower viral levels—perhaps equivalent to Ct of 30 or above—at other labs. This implies that the Innova test performance on high viral loads could have been considerably understated as the viral loads tested were actually much lower than initially measured.

The best-performing antigen test identified, the BinaxNOW antigen test, would have the following performance on a sample of 1000 air passengers with a prevalence rate of 1%, which is the prevalence rate reported by a number of airport testing schemes, including the testing centre at Frankfurt Airport³⁴ and a study undertaken at Toronto-Pearson Airport.³⁵ In some testing schemes reviewed (e.g. Iceland, Jersey), prevalence rates were even lower.³⁶

³⁰ The Ct value is a measure of the viral load an individual carries. Low Ct values are associated with high viral loads.

³¹ Guglielmi, G. (2021), 'Rapid coronavirus tests: a guide for the perplexed', *Nature*, 9 February.

³² Lindner, A.K. (2021), SARS-CoV-2 patient self-testing with an antigen-detecting rapid test: a head-to-head comparison with professional testing, *Medrxiv*.

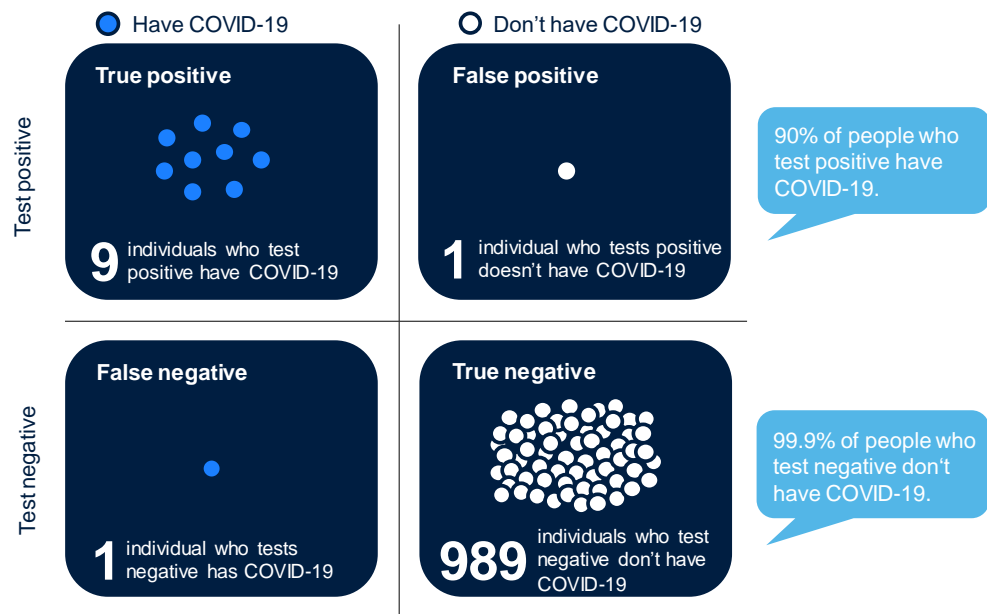
³³ Guglielmi, G. (2021), op. cit.

³⁴ More recent data from 1 March 2021 shows even lower prevalence rates of 0.45% at Frankfurt Airport. For more details see Centogene website: <https://www.centogene.com/covid-19/test-centers/frankfurt-airport.html>.

³⁵ McMaster University (2020), 'Interim report shows results of COVID-19 tests for arriving international travellers', 17 November, <https://brighterworld.mcmaster.ca/articles/interim-report-shows-results-of-covid-19-tests-for-arriving-international-travellers/> (Accessed 17 March 2021)

³⁶ Oxera (2020), 'Review of case studies of effectiveness of testing schemes', 2 November.

Figure 2.8 Implications of antigen testing for 1000 air passengers



Source: Oxera and Edge Health based on Watson, J., Whiting, P. and Brush, J. E. (2020), 'Interpreting a covid-19 test result', *thebmj*, **369**, available at: <https://www.bmj.com/content/369/bmj.m1808> (last accessed 17 March 2021).

This indicates that of 1000 travellers, one individual who is infected with coronavirus would not return a positive test result.

Results change if we consider a less sensitive antigen test such as the SD Biosensor, which is included on the EU commonly approved list of antigen tests. This test has been found to have a sensitivity of 62% (see Table A1.1). Using the traveller figures and prevalence rates presented above, the test would not detect four (instead of one) infected travellers. Although this means that four times as many infected passengers are missed, the low overall prevalence means that the absolute numbers would still be very low.

2.3 Alternative testing technologies

In addition to the main test types set out above, there are a number of other testing technologies that are less frequently used. These are as follows:

- **TMA** (transcription-mediated amplification), which is an RNA-based—i.e. molecular—test such as PCR and LAMP. TMA or transcription-mediated amplification is another technique that can be used to amplify the RNA to a detectable level;³⁷
- **digital PCR**—the key difference between dPCR and traditional PCR lies in the method of measuring amounts of nucleic acids, with the former being a more precise method than PCR, though also more prone to error. A 'digital' measurement quantitatively measures a certain variable, whereas an 'analogue' measurement extrapolates certain measurements based on measured patterns;³⁸
- **CRISPR**—the method is based on the gene scissors CRISPR. Like PCR, the method uses a short RNA molecule to find the gene of interest. In

³⁷ Guglielmi, G. (2020), 'Fast coronavirus tests: what they can and can't do', *Nature*, 16 September.

³⁸ LabMedicineBlog (2020), 'COVID-19 Testing Explained', 2 June, available at: <https://labmedicineblog.com/2020/06/02/covid-19-testing-explained/> (last accessed 17 March 2021).

CRISPR, this is a guide RNA (crRNA). Once the crRNA has attached to the viral gene, it is cut by the enzyme Cas13 (the actual gene scissors). In the same step, a reporter RNA is released that carries a fluorescent marker. This is made to glow by a laser. The colour can then be picked up by a camera. The intensity of the fluorescence provides an indication of the number of viruses contained in the reagent. The first CRISPR test to detect an infection with SARS-CoV-2 was admitted by the US drug regulator FDA for emergency use in May 2020;³⁹

- **SARS-CoV-2 proteome peptide test**—a type of antibody test that analyses antibody interactions at amino acid resolution by spotting peptides representing full-length SARS-CoV-2 proteins.⁴⁰

For the most part, these tests have been developed around the same time as antigen tests. However, because they are more expensive or difficult to implement, they have not been as widely used. There are also fewer academic studies on these tests and therefore it is difficult to compare their accuracy to the other existing technologies. It is therefore not clear that these technologies will have a greater role in testing international travellers in the near future.

2.4 Summary: comparison of testing technologies

Table 2.3 below provides an overview of the main testing technologies discussed above: PCR, LAMP, antigen and antibody. We compare these technologies across a variety of dimensions ranging from more technical parameters, such as sensitivity and specificity, to more practical considerations such as affordability and availability.

It is important that all of these factors are taken into account when deciding on an appropriate testing regime for a specific setting. As the European Commission highlights, the performance of a test needs to be evaluated based on the purpose of the device. As such, a test that is most suitable for diagnosis might not be practical for fast-track screening.⁴¹

A comparison of the most widely used testing technologies reveals the following implications for their use for departure/arrival screening at the airport.

- PCR testing is the most precise technology for the detection of the SARS-CoV-2 virus, but it is not feasible for on departure tests or on arrival testing given the time it takes to process. The processing time may also create issues in using these tests for transfer passengers if they need to show a valid test from 72 hours prior to departure for the second part of their journey.
- In addition, there are questions about the capacity of PCR testing and facility requirements (i.e. laboratory settings to process tests) to accommodate large volumes of travellers as international travel restarts (see section 3).
- Antigen testing has a lower sensitivity, but is able to identify the most infectious population. Given that it does not require significant equipment, it is most suited for a seamless integration into the passenger flow at the

³⁹ Guglielmi, G. (2020), 'First CRISPR test for the coronavirus approved in the United States', *Nature*, 11 May.

⁴⁰ Wang, H. (2020), 'SARS-CoV-2 proteome microarray for mapping COVID-19 antibody interactions at amino acid resolution', *BioRxiv*, available at: <https://www.biorxiv.org/content/10.1101/2020.03.26.994756v1> (last accessed 24 March 2021).

⁴¹ European Commission (2020), 'Communication from the Commission: Guidelines on COVID-19 in vitro diagnostic tests and their performance', 15 April.

airport. Low prices also mean that it is more likely to assist with the restart of travel if tests are required at the origin and/or destination.

The following section examines the applicability of PCR and antigen tests to the aviation setting in greater detail.

Table 2.3 Comparison of testing technologies

	RT-PCR	RT-LAMP	Antigen testing	Antibody testing
Turnaround time	Moderate: from several hours to >2 days. Between 28 May 2020 and 13 January 2021, the median time taken to receive a test result at regional test sites in England was 25 hours.	Fast: from 20 minutes	Fast: from 15 minutes	Depends: from 15 minutes (lateral flow) to several days (laboratory test)
Cost/test	Moderate to high: ~£75–£200/test	Moderate to high: ~£80–£90/test	Cheap to moderate: ~£15–£80/test	Moderate: ~£65/test
Benefits	Most precise testing technology for detecting current infection with SARS-CoV-2	Easier to handle than PCR and quicker to return results as no laboratory setting is required for evaluation of the test	Enables fast, low-cost, decentralised access to direct testing for the virus, relieving the burden on the laboratory testing system	Best biomarker for estimation of the number of people previously infected: enables more accurate estimates of case fatality rates, serial sampling can be used to estimate incidence
Disadvantages	Slow turnaround time, insufficient laboratory testing facilities, not practicable for airport testing	Considerable equipment needed, which restricts the usefulness in certain settings, such as at the airport	Potentially low sensitivity—i.e. relatively high false negative rate—especially in asymptomatic population with certain types of tests	Limited applicability to travel setting because the test is not suited to detect current infection
Availability of test/testing capacities	Varies by country, but generally low to moderate	Varies by country, but generally low to moderate	High	High
Intended use	Detect current infection	Detect current infection	Detect current infection	Detect past infection
Analyte detected	Viral Ribonucleic Acid (RNA) (viral genetic material)	Viral Ribonucleic Acid (RNA) (viral genetic material)	Viral Antigens (viral proteins)	Antibodies (IgA, IgM, IgG or in combination)

	RT-PCR	RT-LAMP	Antigen testing	Antibody testing
Specimen type	Nasal, nasopharyngeal, sputum, saliva	Nasopharyngeal swabs, oropharyngeal swabs, anterior nares swabs, nasal swabs, nasopharyngeal washes/aspirates or nasal aspirates, as well as bronchoalveolar lavage specimens	Nasal, nasopharyngeal	Fingerstick blood, venous blood; potentially oral fluid
Test sensitivity	Generally high: ~95% (in laboratory conditions)	Varies by test, generally moderate to high: ~70–95%	Varies by test: 28–89% for a mixed population of asymptomatic and symptomatic individuals; higher sensitivity for symptomatic individuals and samples with higher viral load	Varies by test, generally high: sensitivity of >99% when tests for different types of antibodies are combined.
Test specificity	High: ~98–99%	High: >99%	High: 93.1–100%	High: 100%
Test complexity	Varies by test, but generally complex with laboratory setting necessary	Easier than PCR, no laboratory setting necessary, but specific equipment required.	Relatively easy to use, home and point of care use possible	Relatively easy to use, home and point of care use possible

3 Comparison of testing technologies for use in a travel setting

3.1 Introduction

The testing technologies described in the previous section are used in a number of different contexts for testing individuals for COVID-19. RT-PCR tests are the most commonly used tests for air travel, although antigen tests are increasingly being used across a number of jurisdictions. Antigen tests have also been widely used in the UK to test truck drivers, schoolchildren, and university students, and by many sporting leagues around the world. UK government data shows that since the week of 21 January 2021 more antigen than PCR tests were conducted in the UK. In the first week of March 2021, more than 6m antigen tests were administered compared to just above 1m PCR tests.⁴²

This section considers the testing technologies set out in the previous section in the context of testing air passengers. We first set out the types of tests required for international travellers across a number of jurisdictions. We then highlight a number of issues that are relevant in determining the optimal testing approach for air travellers.

3.2 The travel context: which tests are required?

Table 3.1 sets out an overview of a number of countries where there are requirements for pre-departure testing and the types of tests that are permitted in order to gain entry. A number of countries reviewed accept antigen testing as pre-departure tests. In two of these cases (UK and Germany), the antigen tests used need to meet WHO performance standards of $\geq 97\%$ specificity and $\geq 80\%$ sensitivity. We note that in some of these countries, tests are also required on arrival.

Table 3.1 Overview of test requirements for international travellers, as of March 2021

Country	Accepted pre-departure coronavirus test	Post-arrival tests required
Canada	Travellers need to take a molecular test (such as PCR or LAMP) within 72 hours of departure. Antigen tests are not allowed	Travellers are tested at arrival and need to quarantine at a hotel while waiting for test results. A second test needs to be taken at day ten, but a release from quarantine is only possible after 14 days
France	Travellers from certain countries (referred to as the European space) ⁴³ are required to take a PCR test 72 hours before boarding. In exceptional cases, if a PCR test cannot be carried out, antigen tests are accepted	Travellers from outside the European space are required to self-isolate for seven days after which they can be released with a PCR test
Germany	Travellers from high-incidence or virus variant areas are required to present a PCR, LAMP, TMA or antigen test taken at most 48h prior to departure provided it meets the WHO performance standards of $\geq 97\%$	Travellers need to quarantine for ten days but can end quarantine with a negative PCR test after five days

⁴² Department of Health & Social Care (2021), 'Weekly statistics for rapid asymptomatic testing in England: 4 March to 10 March 2021', 18 March. Last accessed 25 March 2021 from: <https://www.gov.uk/government/publications/weekly-statistics-for-nhs-test-and-trace-england-4-march-to-10-march-2021/weekly-statistics-for-rapid-asymptomatic-testing-in-england-4-march-to-10-march-2021>.

⁴³ The European space consists of the following countries: European Union Member States, Andorra, the Holy See, Iceland, Liechtenstein, Monaco, Norway, San Marino and Switzerland.

	specificity, $\geq 80\%$ sensitivity. Travellers from other risk areas must have a test result no later than 48 hours after entry	
Italy	Travellers from most European countries need to take a PCR, LAMP or antigen test 48h before arrival. Travellers from the UK must perform an antigen or PCR test 72h prior to arrival and another one at arrival	Travellers from the UK must self-isolate for 14 days regardless of their test results. Travellers from most European countries do not need to self-isolate.
India	Travellers need to take a PCR test 72 hours before boarding	Travellers are screened for symptoms on arrival and might need to quarantine at an institutional facility or privately depending on their country of origin
Netherlands	Travellers from high-risk areas must perform a molecular test (such as PCR or LAMP) 72 hours before arrival. Travellers need to additionally take an antigen test 24 hours prior to boarding	Travellers need to quarantine for ten days but can end quarantine with a negative test after five days
Portugal	Travellers from most European countries and low-risk areas can enter Portugal with a negative PCR test result taken 72 hours before boarding	Travellers from European high-risk countries ⁴⁴ need to self-isolate for 14 days after entry
Spain	Travellers arriving from specific countries must present a medical certificate with a negative molecular test result (such as PCR or TMA) taken at most 72 hours before arrival. Travellers with a positive test result can enter as long as they can prove that they have recovered from COVID-19 and are not contagious anymore	
UK	Travellers need to take a coronavirus test in the three days before arriving to the UK. Tests that meets WHO performance standards of $\geq 97\%$ specificity, $\geq 80\%$ sensitivity is accepted	Travellers need to quarantine for ten days and take two coronavirus tests. Travellers from lower-risk countries can end quarantine with a test after 5 days (test to release)
US	Travellers need to take a coronavirus test (such as PCR, LAMP or antigen) in the three days before departure	Travellers must self-isolate for seven days and get tested three to five days after arrival

Note: The information above refers to the policies in place as at 16 March 2021.

Source: Oxera and Edge Health based on government/health authority guidelines.

3.3 Antigen tests detect the most infectious travellers

Antigen tests have a high specificity, but a lower sensitivity compared to PCR tests. For this reason, travellers are often required to be tested using methods such as PCR or LAMP.

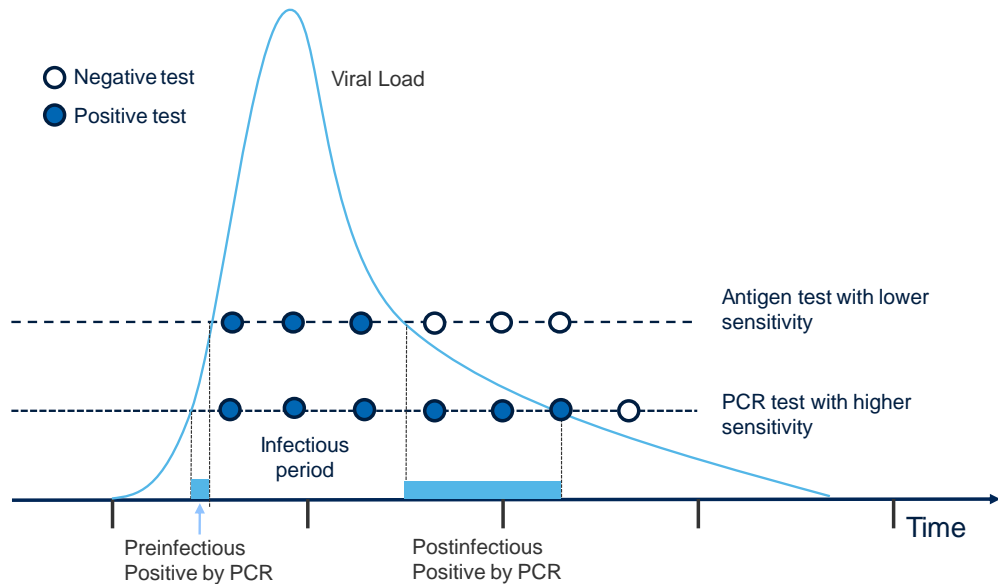
The lower sensitivity of antigen tests, particularly at early stages of an infection, raises concerns among some specialists that the use of antigen tests will miss infectious people and might result in renewed outbreaks in settings with largely controlled coronavirus transmission. Other academics view the lower sensitivity of antigen tests as an advantage, because some people who receive positive PCR test results are infected, but are no longer able to spread the virus to others. Therefore, antigen tests may be better able to identify the most infectious people. As Guglielmi from *Nature* puts it, antigen tests can be ‘thought of as tests of infectiousness, not of infection’.⁴⁵

⁴⁴ Countries with an incidence rate of 500 cases or more per 100,000 inhabitants in the last 14 days are classified as high-risk countries.

⁴⁵ Guglielmi, G. (2021), op. cit.

Indeed, a number of papers highlight that antigen tests might be the most suitable testing method to detect the most infectious population. *Nature*, for instance, concludes that antigen tests return positive results when a person is most infectious, while PCR-based tests can be positive long after a person stops being infectious. Figure 3.1 below visualises this effect.

Figure 3.1 Accuracy of antigen and PCR tests over time



Source: Oxera and Edge Health, based on Michael et al. (2020).

While it seems to be clear that antigen tests perform better on people with higher viral loads—as well as on symptomatic patients—the levels of viral loads that coincide with infectiousness (i.e. the viral load threshold below which a person is no longer contagious) has not yet been determined.

The connection between infectiousness and symptoms seems to be slightly clearer. Although previous research from August 2020 had shown that asymptomatic patients had similar viral loads to symptomatic individuals,⁴⁶ recent research shows that this might not be the case. A meta-analysis from December 2020 has found that asymptomatic individuals are less infectious: the relative risk of asymptomatic transmission was 42% lower than that for symptomatic transmission.⁴⁷ Similarly, another recent study from January 2021 shows that asymptomatic individuals carrying the virus had 69.6% lower odds of infecting another household member compared to those reporting symptoms.⁴⁸

Although research has shown that the initial viral loads of asymptomatic individuals were similar to patients with symptoms, asymptomatic patients seem to get rid of the virus faster and are infectious for a shorter period. This might be one of the reasons why antigen tests perform less well on asymptomatic individuals.⁴⁹

⁴⁶ Lee, S. et al. (2020), 'Clinical Course and Molecular Viral Shedding Among Asymptomatic and Symptomatic Patients With SARS-CoV-2 Infection in a Community Treatment Center in the Republic of Korea', *JAMA Internal Medicine*, **180**:11, pp. 1447–52.

⁴⁷ Byambasuren, O. et al. (2020), 'Estimating the extent of asymptomatic COVID-19 and its potential for community transmission: Systematic review and meta-analysis', *Official Journal of the Association of Medical Microbiology and Infectious Disease Canada*, **5**:4, pp. 223–34.

⁴⁸ Bi, Q., et al. (2020), 'Household Transmission of SARS-CoV-2: Insights from a Population-based Serological Survey', *MedRxiv*.

⁴⁹ Nogrady, B. (2020), 'What the data say about asymptomatic COVID infections', *Nature*, 18 November.

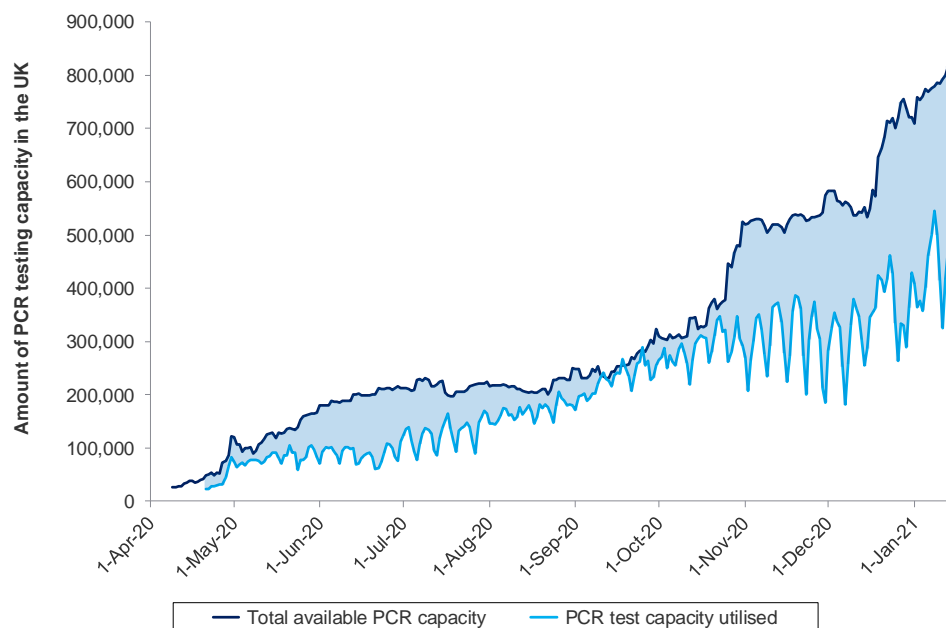
3.4 PCR testing capacities may not be sufficient to test a significant proportion of 2019 air passengers

Although PCR tests have been shown to have the highest accuracy of all diagnostic tests when performed in optimal conditions, PCR testing capacities are limited by equipment, expertise, and reagent. Although testing capacities have been ramped up significantly in a number of jurisdictions, they are unlikely to be sufficiently large to test even a fraction of the 2019 travelling population.

To put this in context, the UK government regularly publishes data on PCR testing capacities and tests conducted. Figure 3.2 below shows how testing capacities have increased from around 100,000 in May 2020 to about 800,000 in January 2021. While NHS testing capacity is not currently used for testing international travellers, and it is likely going forward that only private testing could be used for international travel, there is limited data available on the extent of private testing capacity. Therefore, we show below that even if the current NHS capacity could be utilised for air passengers, this would only cover a fraction of travel volumes.

Figure 3.2 plots the total PCR testing capacity and PCR tests conducted in England between April 2020 and January 2021. Shaded in light blue is the proportion of NHS PCR testing capacity that is currently not being used.

Figure 3.2 Development of PCR testing capacities in England, April 2020 to January 2021



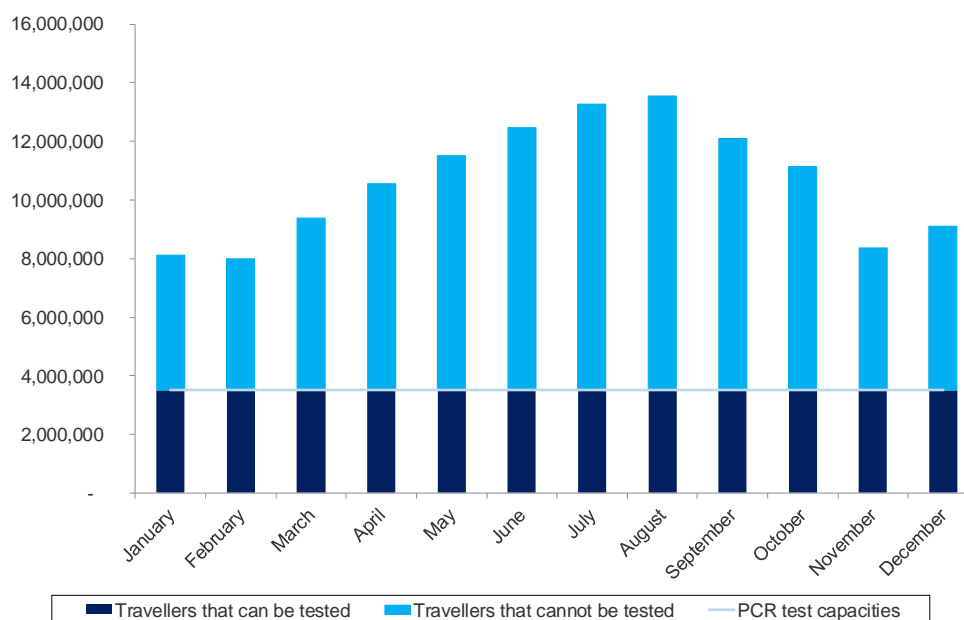
Source: Analysis by Oxera and Edge Health, based on UK government testing statistics from <https://coronavirus.data.gov.uk/details/testing> (last accessed February 2021).

For the time period observed, the average daily unutilised PCR testing capacity in the UK was 117,244 which equals about 3.5m unutilised PCR tests per month.

Figure 3.3 compares the unutilised PCR testing capacities with the monthly number of UK residents that travelled abroad in pre-pandemic times (i.e. 2019). It plots the number of outbound UK travellers that would need to get tested with a PCR test if such a test was a requirement for travelling abroad.

Even if 3.5m tests per month could be used for air passengers, these would only cover approximately 25% of 2019 traveller volumes.

Figure 3.3 Comparing outbound UK air travellers and current PCR testing capacities if air travel returns to 2019 levels



Source: Analysis by Oxera and Edge Health, based on data from the Civil Aviation Authority and UK government testing statistics from <https://coronavirus.data.gov.uk/details/testing> (last accessed 17 March 2021).

It is likely that considerable investment would be needed by the private sector to ensure that all international travellers can be PCR tested before departure or following arrival. For example, the UK test and trace policy was assigned a budget of £22bn in 2020. Of the £15bn of funding confirmed prior to the November 2020 Spending Review, about 85% (or £12.8bn) was allocated to testing.⁵⁰ However, there is no clarity regarding how long testing will continue, which may limit the incentives for the private sector to invest.

3.5 PCR and antigen tests are likely to be effective on Variants of Concern

The coronavirus variant B1.1.7, which was first reported in Britain, contains 17 recent mutations or deletions in areas that code for amino acids (which are the building blocks of proteins). Mutations in these areas can result in changes to the shape of viral proteins and in turn how they interact with host cells and antibodies. Eight of those mutations—those that researchers are most concerned about—are mutations to the spike protein that the virus uses to attach to cells, and which is its way of getting inside the cell.⁵¹ The South African and Brazilian variants also contain nine and ten mutations to the spike gene respectively.⁵²

Virus variants are detected by ‘genome sequencing’, which enables scientists to obtain a complete breakdown of the genetic information contained in a virus.

⁵⁰ Syal, R. (2020), ‘England’s test and trace repeatedly failed to hit goals despite £22bn cost’, *The Guardian*, 11 December.

⁵¹ Corum, J. and Zimmer, C. (2020), ‘Inside the B.1.1.7 Coronavirus Variant’, *The New York Times*, 18 January.

⁵² FIND (2020), ‘The Impact of Novel Variants of Sars-Cov-2 on Diagnostic Testing’, available at: <https://www.finddx.org/covid-19/novel-variants/> (last access 17 March 2021).

The equipment needed to perform genome sequencing differs from that used for PCR and antigen testing. Genome sequencing (and the subsequent analysis of sequencing data) is also significantly more time-consuming than PCR or antigen testing and can take several days.⁵³ Hence, neither of these tests can *help identify new variants*. However, a technique called mutation-specific PCR genotyping enables scientists to determine if a sample contains a specific virus variant.⁵⁴

The most relevant function of a PCR or antigen test remains the detection of COVID-19, irrespective of the variant. For instance, if an individual tests positive for COVID-19 with an antigen test, then another test could be undertaken for the purposes of genome sequencing. Therefore, researchers and health authorities have put a lot of effort into understanding if PCR and antigen tests can detect the virus variants.

The US Food and Drug Administration ('FDA') explains that false negative results can occur if a mutation happens in the part of the virus' genome or part of the protein assessed by the test.⁵⁵ Some specialists have maintained that PCR tests will not be affected by the virus mutations because they pick the most conserved areas of the virus RNA. The Foundation for Innovative New Diagnostics ('FIND') finds that the majority of tests currently used in primary detection of SARS-CoV-2 will not be affected.⁵⁶

However, health authorities such as the FDA have started re-evaluating the tests previously approved.⁵⁷ The FDA has identified three molecular tests that might be affected by the new SARS-CoV-2 variants, but this impact does not seem to be significant.⁵⁸

Specialists have suggested that most antigen tests are at low risk of being affected by the virus variants. This is because most antigen tests assess the nucleocapsid protein, which is the part of the protein at the centre of the virus that contains the viral RNA. The nucleocapsid protein is much more stable than the spike protein and is therefore unlikely to be affected by current or future virus mutations.⁵⁹

Furthermore, Public Health England ('PHE') empirically assessed if a selection of antigen tests are able to detect the British variant. The tests evaluated were Abbott Panbio, Fortress, Innova, Roche/SD Biosensor nasal swab, and Surescreen. PHE confirmed that all five antigen tests successfully detected the new variant and that their performance was not negatively affected. Preliminary analyses show that the British and Brazilian variants have been associated with higher viral loads compared with the existing COVID-19 virus.⁶⁰ According

⁵³ Charité: Universitätsmedizin Berlin, 'FAQs on SARS-CoV-2'—for further details, see: https://www.charite.de/en/clinical_center/themes_hospital/main_topic_coronavirus/faqs_on_sars_cov_2/ (last accessed 17 March 2021)

⁵⁴ Charité: Universitätsmedizin Berlin, op. cit.

⁵⁵ Fornell, D. (2020), 'FDA Says New COVID Virus Mutation May Cause False Negatives', DAC (Diagnostic and Interventional Cardiology), 8 January.

⁵⁶ This is because RT-PCR tests targeting the spike gene are not widely used for primary detection, and many PCR tests target multiple genes. World Health Organization (WHO) (2021), 'Molecular assays to diagnose COVID-19: Summary table of available protocols', available at: <https://www.who.int/publications/m/item/molecular-assays-to-diagnose-covid-19-summary-table-of-available-protocols> (last accessed 4 January 2021).

⁵⁷ Kent, C. (2021), 'Covid-19 variants: will the reliability of tests be affected?', *Medical Device Network*, available at: <https://www.medicaldevice-network.com/features/covid-19-variant-tests/> (last accessed 17 March 2021).

⁵⁸ Fornell, D. (2020), op. cit.

⁵⁹ Kent, C. (2021), op. cit.

⁶⁰ New and Emerging Respiratory Virus Threats Advisory Group (NERVTAG) (2020), 'NERVTAG meeting on SARS-CoV-2 variant under investigation VUI-202012/01', 18 December, available at: <https://khub.net/documents/135939561/338928724/SARS-CoV->

to FIND, detection rates for these variants with antigen tests may actually *increase* due to increased concentration of antigen in samples.

4 Modelling the effectiveness of testing technologies on air passengers

4.1 Introduction

In this section, we model the efficacy of screening infectious travellers with a single test. We model the efficacy of the main diagnostic testing technologies reviewed in the previous sections: PCR, LAMP, and antigen tests. We focus on the UK as an example destination and the EU and USA as example origins, though the analysis can be broadened out to consider other locations as well.

4.2 Methodology

To undertake our analysis, we have updated our previous modelling work, which was based on a paper published by the London School of Hygiene & Tropical Medicine (LSHTM) in July 2020,⁶¹ to include antigen testing. We have also updated our model to reflect the most recent evidence on air passenger compliance with quarantine and syndromic screening.⁶² In addition, we model estimates of infection risk in the UK domestic population. Each testing scheme is then benchmarked relative to a baseline scenario with no testing⁶³ and infection risk in the domestic population.

The rest of this section is structured as follows.

- In section 4.2.1, we provide an overview of the modelling framework.
- In section 4.2.2, we set out the testing schemes that we have modelled.
- In section 4.2.3, we explain the updates we have made to key assumptions from our previous modelling work.
- Finally, in section 4.2.4, we discuss how we measure infection risk.

For a detailed overview of all of the assumptions used in our modelling, see appendices A2 and A3.

4.2.1 Overview of the modelling framework

The purpose of our analysis is to evaluate the effectiveness of different testing schemes and quarantine policies at preventing individuals with a SARS-Cov-2 infection 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.

As part of this analysis we use a measure of **infectious days**. By 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, than considering infected passengers. For example, 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).

⁶¹ See Oxera and Edge Health (2020), 'Modelling the effectiveness of airport testing regimes, 6 November. For LSHTM work see: Clifford et al. (2020), 'Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers', 25 July.

⁶² Defined as passengers either self-screening or being screened at the airport because of symptoms consistent with COVID-19.

⁶³ The baseline scenario is outlined in Table 4.1. The baseline scenario includes syndromic screening alone; see section 4.2.3 for further details and definitions of syndromic screening.

We use Monte Carlo methods to simulate:

- the proportion of passengers that intend to travel who are expected to be infected, based on infection prevalence at the departure location;⁶⁴
- 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 scenarios are discussed further in section 4.2.3.

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

4.2.2 Modelled testing schemes

Our analysis focuses on single-testing schemes. Single-testing schemes, sometimes in combination with a mandatory quarantine period, have been employed across a number of jurisdictions at different times since the beginning of the pandemic (e.g. UK, USA, Germany). In light of concerns around emerging variants⁶⁵ of SARS-Cov-2, many countries (e.g. Belgium, UK, Canada) have more recently started to require air passengers to provide a negative test no more than 72 hours before departure in addition to tests on arrival.

We model single tests using RT-PCR, RT-LAMP, and antigen technologies at different points during a passenger's journey. We model pre-departure testing 72 hours before departure both with and without a pre-departure quarantine requirement.⁶⁶

Table 4.1 below outlines the testing schemes considered in this analysis.

⁶⁴ Note that this methodology does not account for differing age and comorbidity structures across countries when estimating actual infection prevalence from reported cases.

⁶⁵ For example, the B.1.1.7 variant, first reported in the UK. See section 3.5 for further details.

⁶⁶ Pre-departure quarantine requirement results are included in Appendix A4, Table A4.1.

Table 4.1 Modelled single-testing schemes, by timing of test, testing technology, and minimum quarantine period

Testing scheme	Timing of administering test	Pre-departure quarantine requirement	Testing technology	Minimum post-arrival quarantine period ⁶⁷
Baseline	None	None	None	None
Ten-day quarantine ⁶⁸	None	None	None	Ten days
Before departure	Three days pre-departure	Quarantine for 72 hours pre-departure or no quarantine	RT-PCR RT-LAMP Antigen	None None None
On departure ⁶⁹	At airport, on departure	None	RT-LAMP Antigen	None None
On arrival	At airport, on arrival	None	RT-PCR RT-LAMP Antigen	One day None None
Post-arrival	One to eight days post-arrival	None	RT-PCR RT-LAMP Antigen	2–9 days 1–8 days 1–8 days

4.2.3 Key updates to the assumptions in the analysis

The key assumptions we have updated for this modelling work include the following.

Antigen testing

We have included antigen testing, in addition to presenting the results based on molecular testing (PCR/LAMP). As outlined in our literature review, antigen tests have a wider range of sensitivities compared to molecular testing. This variance is affected by several factors, most notably the brand of test, the viral loads of the population being tested, and testing conditions. Antigen tests tend to have higher sensitivity in the first week following symptom onset (when individuals have higher viral loads),⁷⁰ and sensitivity tends to drop off more quickly than in molecular tests (e.g. PCR/LAMP). Pre-symptomatic and asymptomatic test sensitivity also tend to be lower for most brands of antigen tests.

Quarantine compliance

New survey evidence from the Office for National Statistics (ONS)⁷¹ suggests that quarantine compliance in the UK may be higher than suggested by

⁶⁷ If individuals become symptomatic or test positive for SARS-CoV-2, their quarantine period may be extended.

⁶⁸ Here we benchmark on a ten-day quarantine alone, not a ten-day quarantine in combination with a pre-departure test (as has been recently implemented in the UK), as this report does not focus on the combination of pre-departure testing with other quarantine and testing measures.

⁶⁹ PCR is not considered for on-departure testing, as PCR test turnaround time is generally too long for it to be used in a pre-departure setting.

⁷⁰ Mina et al. (2020) 'Rethinking Covid-19 Test Sensitivity — A Strategy for Containment', 26 Nov.

⁷¹ ONS Survey on non-exempt passenger behaviour available from:

<https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/adhocs/12575nonexemptinternationalarrivalselfisolationbehaviouralsurveytrotuk30septemberto8october2020> (last accessed 21 January 2020).

previous international survey evidence.^{72,73} However, this ONS data also suggests that compliance decreases over the quarantine period—compliance stays relatively constant until day eight, but it then drops by roughly 14% by day 13. There are three levels of compliance included in the ONS survey: (i) those fully complying with government guidelines; (ii) an intermediate group, which could be regarded as either compliant or non-compliant depending on context (for example, leaving home to get basic necessities); and (iii) those not complying with government guidance. The results of the ONS survey data are included in Table 4.2 below.

Table 4.2 Self-reported quarantine compliance for the UK air passenger population

Days in quarantine	Those who were definitely compliant with government guidelines	Those who may have been compliant with government guidelines	Those who were definitely not compliant with government guidelines
5	72%	20%	8%
8	71%	20%	9%
13	58%	24%	18%

Source: Oxera and Edge Health, based on the Non-Exempt International Arrivals Self-Isolation Behavioural Survey.

In our analysis, we assume that compliance levels are equivalent to the individuals that can definitely be regarded as compliant. While individuals in the second group, who are non-compliant for reasons such as leaving the house to get necessities, may be engaging lower-risk activities than those in the third group who are definitely non-compliant, we account for the potential risk associated with both groups.⁷⁴

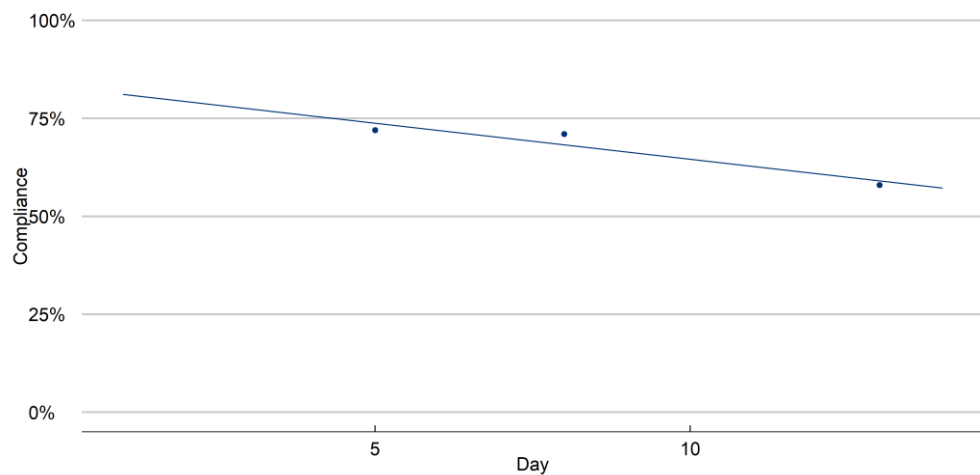
As illustrated in Figure 4.1, we use a linear regression to estimate compliance on each day of quarantine from the available compliance data, which only reports compliance at days five, eight and thirteen.

⁷² Steens A. et.al. (2020), 'Poor self-reported adherence to COVID-19-related quarantine/isolation requests, Norway, April to July 2020.', *Euro Surveillance* 25(37).

⁷³ As compliance is self-reported, individuals may report higher quarantine compliance compared to their actual behaviour.

⁷⁴ The survey also includes some information on the number of times that individuals in quarantine have left their accommodation while quarantining. Most passengers report leaving their place of quarantine only a handful of times. Further work could be undertaken to consider the level of risk from these passengers given the types of activities that they engage in and the number of times they leave their accommodation.

Figure 4.1 Relationship between days in quarantine and compliance



Source: Oxera and Edge Health based on ONS survey data.

Syndromic screening

Syndromic screening refers to the combination of passengers self-screening by choosing not to fly when they develop symptoms, and passengers being prevented from flying at the airport because of their symptoms. The relative efficacy of each testing scheme is benchmarked against a base-case scenario with syndromic screening alone. Earlier modelling from LSHTM assumed that 70% of passengers who were symptomatic at the time of departure would self-select out of flying or be prevented from flying.^{75,76} Since this modelling was undertaken, real-world studies on symptom screening at airports (i.e. passengers being screened for symptoms by airport or government staff) suggest that it is an ineffective measure to identify test-confirmed positive infections.⁷⁷ Therefore, syndromic screening is mainly driven by passengers self-screening and choosing not to fly when they develop symptoms. In our analysis, we consider syndromic screening efficacy to be equivalent to compliance with quarantine upon developing symptoms consistent with COVID-19 based on survey evidence (see Table 4.3 below). As there is an absence of real-world evidence on passenger re-booking behaviour⁷⁸ (i.e. self-screening) when symptomatic, we also present a sensitivity analysis.

Table 4.3 below provides a summary of updated parameters and sources. Appendix A2 provides the full list of modelling assumptions.

⁷⁵ Clifford et al. (2020), 'Strategies to reduce the risk of SARS-CoV-2 re-introduction from international travellers', 25 July.

⁷⁶ Gostic K, et.al. (2020), 'Estimated effectiveness of symptom and risk screening to prevent the spread of COVID-19', *Elife* **9**.

⁷⁷ Dollard, P. et al. (2020), 'Risk Assessment and Management of COVID-19 Among Travelers Arriving at Designated U.S. Airports, January 17–September 13', *MMWR Morb Mortal Wkly Rep*, **69**:45, pp. 1681–5.

⁷⁸ Some of this will be captured in a study that we are conducting with Heathrow where we are using real-world data provided by airlines to assess testing scheme efficacy and passenger re-booking patterns.

Table 4.3 Updated model parameters, including descriptions and sources: air passenger population

Model input	Description
Proportion of infected passengers (prevalence estimates)	<p>Based on prevalence at the passenger’s departure region (either USA or EU). 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 prevalence when the difference in prevalence between the departure and arrival destinations was at its lowest, highest, and median values over the course of 2020.</p> <p>Underlying age/comorbidity structures and passenger demographics not considered.⁷⁹</p>
Number of people intending to fly	<p>Average monthly historical volumes from 2019 scaled to reflect 2020 volumes.⁸⁰</p> <p>To reflect potential future airline volume increases as vaccinations are rolled out, we present potential airline volumes between 10–30% higher than they were in 2020.</p>
Antigen testing sensitivity	<p>Antigen test sensitivity can vary significantly depending on the brand of test used, the population being tested, and the amount of time after infection that the test is administered. We use one of the better performing antigen tests in our analysis. We refer to this test as the FDA-approved antigen test throughout the paper. It has the following reported sensitivities compared to PCR:</p> <ul style="list-style-type: none"> • pre-symptomatic: 80%; • 0–7 days post-symptom onset: 95%;⁸¹ • 8+ days post-symptom onset: 80%; • asymptomatic: 80%.
Air passenger quarantine compliance rate	<p>We extrapolate from data available on air passenger quarantine compliance over time 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 five, 71% of respondents definitely complying with quarantine by day eight, 58% of respondents complying by day 13.⁸² We apply these quarantine compliance rates to both symptomatic and asymptomatic passengers.</p>
Symptomatic quarantine compliance rate	<p>In addition to requirements to quarantine due to travel, in most jurisdictions individuals are also asked to quarantine if they develop symptoms consistent with COVID-19. Therefore, we include quarantining due to symptoms in our model as well. We set this at 18.2% for symptomatic individuals.⁸³ This is based on survey evidence in the UK population from King’s College London.⁸⁴ This is applied to individuals both pre- and post-arrival in their travel destination.</p>

⁷⁹ Russell T. W. et al. (2020), ‘Reconstructing the early global dynamics of under-ascertained COVID-19 cases and infections’, *MedRxiv*.

⁸⁰ Airport data 2020 05 from the UK Civil Aviation Authority. Available from: <https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-Airport-data/Airport-data-2019/> (last accessed 17 March 2021).

⁸¹ Pilarowski, G. et al. (2020), ‘Field performance and public health response using the BinaxNOWTM Rapid SARS-CoV-2 antigen detection assay during community-based testing’, *Oxford University Press for the Infectious Diseases Society of America*.

⁸² ONS Survey (2020), op. cit.

⁸³ Quilty, B. J. et al. (2020), ‘Effectiveness of airport screening at detecting travellers infected with novel coronavirus (2019-nCoV)’, *Eurosurveillance*, 25(5).

⁸⁴ 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).

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.⁸⁵ As a sensitivity analysis, syndromic screening of 70% is included, reflecting early modelling on pre-departure screening.⁸⁶

In addition to updating our model on air passenger testing, we have adapted this modelling framework to estimate infection risk from the UK population in addition to air passengers. This allows us to benchmark the effectiveness of testing schemes, and therefore the risk of air passengers causing domestic spread, to domestic infection risk as well as risk from air passengers in a base-case with syndromic screening alone.

In the updated modelling framework, we assume that people in the UK quarantine for two reasons: upon developing symptoms consistent with COVID-19 (if they are compliant with the requirement—this aligns with symptomatic compliance) or upon receiving a positive test after developing symptoms.⁸⁷ The probability of a person seeking a test when symptomatic is 10.9% as measured by Survey of Adherence to Interventions and Responses.⁸⁸

Table 4.4 Updated model parameters, including descriptions and sources: UK population

Model input	Description
Proportion of infected population (prevalence estimates)	The Office for National Statistics in the UK publishes weekly reports of the percentage of people in the community testing positive for SARS-CoV-2. ⁸⁹ These estimates are made at the national level, which we use to calculate the UK community prevalence.
Proportion of individuals who get tested, if symptomatic	10.9% ⁹⁰
Symptomatic quarantine compliance rate	18.2 % ⁹¹

Assumptions regarding the proportion of symptomatic and asymptomatic passengers and infection evolution are identical across modelling frameworks. See Appendix A3 for a full list of the modelling assumptions.

4.2.4 Measuring testing efficacy

To measure the efficacy of the different testing strategies, we use the metric of *infectious days* screened from entering the community. This metric allows for a

⁸⁵ 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).

⁸⁶ Gostic K, et.al. (2020), op. cit.

⁸⁷ Due in part to case under-ascertainment, the UK’s test-and-trace system is contacting a relatively low proportion of cases as a share of the UK’s overall caseload. For this reason we do not include this in our modelling framework. While the test-and-trace contact rate is improving, we expect the impact of test-and-trace on reducing infectious days spent in the community to be relatively low, in part due to the large proportion of undetected SARS-Cov-2 infections, which we calculate by comparing data from the ONS Infection Survey with confirmed cases.

⁸⁸ 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), September 2020.

⁸⁹ ONS Infection Survey data available from: <https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/bulletins/coronaviruscovid19infectionsurveypilot/previousReleases>, (last accessed 17 March 2021).

⁹⁰ Smith, L. E. et al. (2020), op. cit.

⁹¹ Steens, A. et al. (2020), op. cit.

more comprehensive understanding of infection risk compared to measuring infectious individuals screened, including being able to take account of:

- **differing infectiousness levels for symptomatic and asymptomatic passengers**—symptomatic and asymptomatic individuals have different durations of infectiousness. We model the median number of infectious days for symptomatic individuals as 7.1 and for asymptomatic individuals as 5.3 days (see Appendices A2 and A3);
- **differing quarantine compliance over time**—this metric provides a better view of different scenarios' effectiveness at reducing infection spread once quarantine compliance is introduced, as it accounts for changing compliance levels upon receipt of a positive test or upon developing symptoms.

4.3 Modelling results

In this section we present our modelling results. The efficacy of testing and quarantine schemes are benchmarked to:

- a baseline scenario with no testing (section 4.3.1);
- infection risk in the domestic population (section 4.3.2).

We present the results of our sensitivity analysis in Appendix A4.

4.3.1 Relative efficacy of testing schemes

Table 4.5 below sets out the key results of the analysis.⁹² It presents the percentage of infectious days screened by each testing scheme compared to the base case with syndromic screening alone (i.e. without testing or quarantine). For example, across our simulations, on-departure antigen testing screens 62% of the infectious days that would have entered the community without testing or quarantine requirements. The 90% confidence interval is presented in brackets, based the fifth and 95th percentiles of our simulation results.

⁹² We use the sensitivities reported for the FDA-approved antigen test for our central scenario. We also assume that pre-departure syndromic sensitivity is 18.2%.

Table 4.5 Median percentage of infectious days screened in different testing schemes, compared to the base case

Timing of test	PCR	LAMP	FDA-approved antigen test	No test requirement
Test 72 hours before departure	45% (23–69%)	41% (18–63%)	38% (17–59%)	-
Test on departure	-	65% (43–83%)	62% (39–86%)	-
Test on arrival	72% (53–89%)	65% (43–86%)	63% (40–85%)	-
Test after one day of post-arrival quarantine	76% (59–89%)	71% (52–88%)	69% (48–88%)	-
Test after two days of post-arrival quarantine	78% (63–91%)	75% (60–89%)	73% (55–88%)	-
Test after three days of post-arrival quarantine	79% (63–90%)	76% (61–88%)	75% (57–88%)	-
Test after four days of post-arrival quarantine	77% (60–90%)	76% (60–89%)	74% (58–88%)	-
Test after five days of post-arrival quarantine	74% (57–88%)	75% (59–87%)	74% (57–88%)	-
Ten days of post-arrival quarantine, no testing	-	-	-	62% (41–81%)

Source: Oxera and Edge Health. Assuming 0.182 syndromic screening. 90% confidence intervals are presented in brackets, based on the fifth and 95th percentiles of our simulation results.

Across the different testing schemes considered, antigen tests screen a comparable proportion of infectious days to PCR and LAMP tests. For example, a PCR test on arrival screens 72% of infectious days, while a LAMP test screens 65% and an antigen test screens 63% of infectious days. The differences in performance between PCR, LAMP, and the FDA-approved antigen test narrow further with the introduction of a post-arrival quarantine period. A PCR test three days after arrival screens 79% of infectious days compared to 75% for antigen, and PCR and antigen tests both screen 74% of infectious days five days after arrival.

These results are driven by the type of antigen test used, as the FDA-approved test has a high reported sensitivity.⁹³ Therefore, the results may differ if a different antigen test is used (see sensitivity analysis in Appendix A4). In addition, this analysis uses the metric of infectious days. As outlined in section 3.3, individuals can test positive with a PCR test even after they are no longer infectious.⁹⁴ During this post-infectious window antigen testing has a lower performance than PCR. However, the lower performance of antigen testing when someone is no longer infectious does not impact infectious days screened or onward transmission risk.

Tests administered 72 hours before departure screen the smallest proportion of infectious days, and testing on departure is found to be much more effective. The FDA-approved antigen test administered on departure screens 62% of infectious days, a comparable proportion to a ten-day quarantine requirement.

⁹³ 95% that of PCR during the first week of symptoms and 80% that of PCR in the second week of symptoms and for asymptomatic individuals.

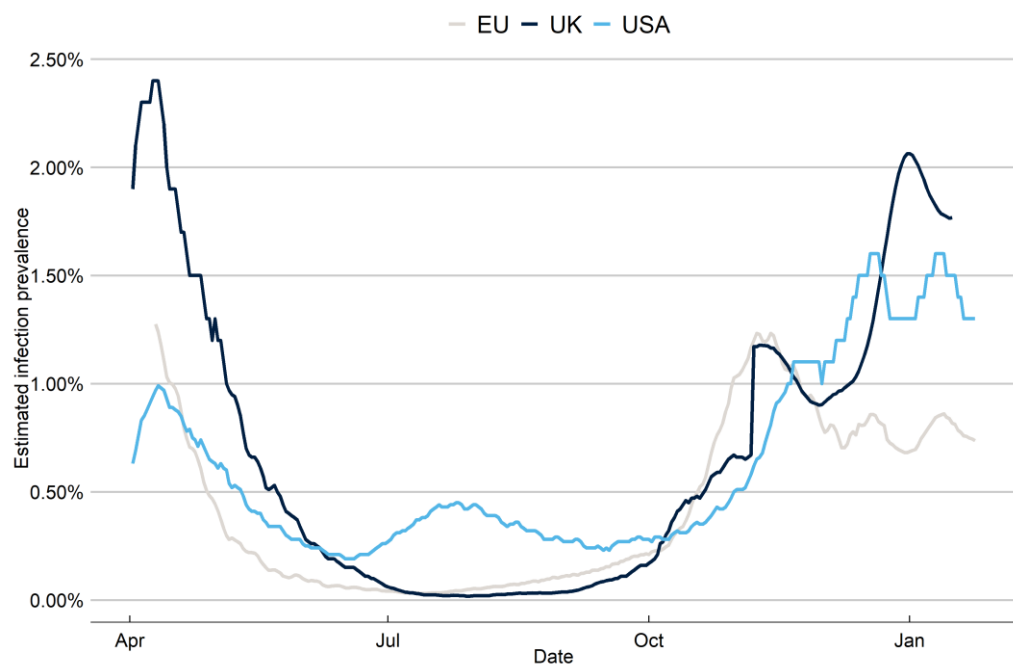
⁹⁴ Mina, M.J. et al. (2020), op. cit.

4.3.2 Infection risk from air passengers relative to domestic infection risk in the destination country

In addition to comparing infectious days screened by each testing scheme to a base case without testing or quarantine, it is important to contextualise risk in terms of domestic prevalence levels. For example, risk tolerance may differ depending on whether domestic prevalence is higher or lower than the origin country. As vaccinations continue to be rolled out in different destinations, the COVID-19 risk to domestic populations will continue to decrease. However, for the purposes of the analysis below, we do not take vaccination into account.

To illustrate the relative risk depending on differences in prevalence levels in departure and arrival locations, we use estimated infection prevalence in the UK, EU, and USA over the course of 2020–21. We then identify the dates at which prevalence rates in the USA or EU were lowest and highest compared to the UK, and the median difference. These points represent reasonable scenarios for SARS-Cov-2 prevalence differences between origins and destinations over time.

Figure 4.2 Relative estimated infection prevalence between origin and destination regions



Source: Oxera and Edge Health, based on modelling from Russell et Al. (2020) and estimates from the ONS infection survey (for UK prevalence past Nov 2020, where estimates become available for all four nations).

For each prevalence scenario—i.e. when prevalence values in the US/EU were lowest compared to the UK, highest compared to the UK, and the median difference—we compare infectious days released by 10,000 air passengers to days released by 10,000 people in the domestic population. We present our findings in Table 4.6 below for three testing schemes: an antigen test administered 72 hours before departure, an antigen test administered on arrival (which is also representative of antigen tests administered on-departure in terms of efficacy), and an antigen test administered three days after arrival. We use the USA as an example origin and the UK as the example destination.

We find that across testing schemes, air passengers consistently present a lower infection risk relative to the domestic population. This is the case even in the scenario where the USA prevalence is highest relative to the UK and a single antigen test is administered before departure (i.e. the least effective testing scheme). We find that infectious days released by air passengers are 33% of those released by the same number of individuals in the domestic population.

Table 4.6 Proportion of infectious days from air passengers from the USA as a share of infectious days from the UK population, per 10,000 population

Relative prevalence difference	Date	72 hours before departure	On arrival	On day three
USA prevalence highest compared to UK	14/12/2020	33%	21%	14%
Median prevalence difference	05/10/2020	26%	15%	10%
USA prevalence lowest compared to UK	05/04/2020	8%	5%	3%

Source: Oxera and Edge Health. Infectious days are calculated per 10,000 population of either air passengers or the domestic population.

The very small contribution of infectious days from air passengers is evident, even when US prevalence was higher than that of the UK (as at 14 December 2020). For example, given average passenger volumes between the USA and the UK of 52,000⁹⁵ in 2020 (equivalent to approximately 26,000 monthly inbound passengers), air passengers not screened by the antigen test on arrival would account for 0.008% of total infectious days in the UK. This amounts to eight infectious days per 100,000 in the community. Even if air passenger volumes from the USA recovered to 30% of 2019 volumes (approximately 277,300 monthly inbound passengers), air passenger infectious days would be 0.085% of total infectious days in the community—i.e. only eight infectious days per 10,000 in the community.

In effect, even in the absence of testing, potential infectious days from air passengers coming from the USA or the EU represent a small share of the overall potential infectious days in the UK community.⁹⁶ Therefore, when prevalence rates are already high or the population is vaccinated, the relative risk of air passengers spreading infection may be lower. However, when case numbers are low (in an unvaccinated population) or there is concern about introducing new variants from certain destinations to the community, testing remains an effective tool to screen air passengers. Testing can also be used to identify passengers for further sequencing tests, as monitoring SARS-Cov-2 variants becomes a priority.

4.4 Conclusion

Across different testing schemes considered—e.g. before departure, on arrival, and post arrival—the antigen test screens a similar proportion of infectious days compared to PCR and LAMP tests. For longer quarantine periods, the antigen test performs almost identically to the other test technologies. This is because the post-arrival quarantine period allows infected passengers' infections to progress past their incubation period when most individuals will be detectable even at lower test sensitivities.

⁹⁵ Airport data 2020 05 from the UK Civil Aviation Authority, op. cit.

⁹⁶ Based on relative prevalence values from 2020–21.

Antigen testing administered on-departure or on-arrival screen a similar proportion of infectious days compared to a ten-day quarantine alone when quarantine compliance is taken into account, and more infectious days than a 72-hour pre-departure test. However, on-departure and on-arrival tests at the airport may present operational challenges for airports and airlines, in terms of passenger flow and scaling capacity as demand for air travel recovers.⁹⁷ Antigen tests administered the day before departure would be expected to screen a similar proportion of infectious days to on-departure or on-arrival testing, with fewer operational challenges.

While the testing schemes considered have varying efficacies in terms of screening infectious days in the air passenger population, they all lead to lower risk levels compared to infectious days already in the UK domestic population. The relative risk to the UK domestic population is expected to decrease further as vaccinations are rolled out.

⁹⁷ We are considering this in work we are currently undertaking for Heathrow Airport.

5 The economic impact of the cost of testing

5.1 Introduction

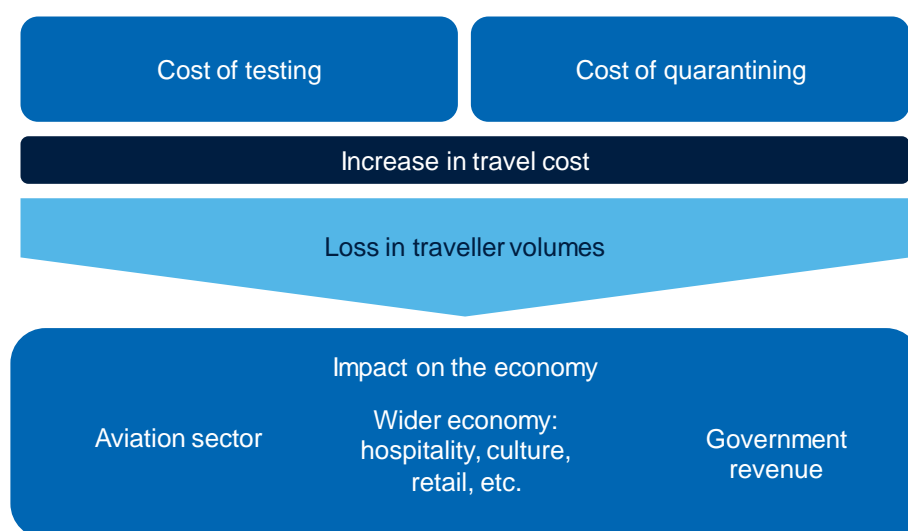
As discussed in section 3, travel protocols, such as testing and quarantine requirements for international passengers, have been introduced in most jurisdictions. These requirements can significantly increase the cost of travel, leading to reduced passenger volumes and impacts on the economy.

Figure 5.1 below shows the mechanisms through which testing and quarantine policies impact air passenger volumes and the economy. Testing requirements lead to direct costs for passengers, often as part of both the outbound and the inbound journey. Passengers also incur the opportunity cost of the time spent determining the relevant testing regime, organising the test(s) and performing tests in line with government requirements. Similarly, quarantine requirements might create direct costs for passengers—e.g. if they need to quarantine at a hotel at their own cost—or in the form of lost work days, annual leave, or reduced productivity while working from home.

Overall, testing and quarantine measures create additional costs that are likely to lead to fewer people travelling, and people travelling less often. The amount by which travel volumes will decrease depends on: (i) the percentage increase in travel cost; and (ii) the price elasticity of demand.

A loss in passenger volumes will also have an impact both on the aviation sector through lost revenues (e.g. for airlines, airports, air navigation service providers), and on governments through lost tax revenues. Less international travel also has an impact on other sectors of the economy—for example, fewer hotel accommodations are booked, fewer touristic sites are visited and fewer restaurants are frequented.

Figure 5.1 Impact of testing and quarantine regimes on passengers and the economy



Source: Oxera and Edge Health.

In absolute terms, all travellers to destinations with similar requirements are affected in the same way—i.e. they all need to pay for tests and/or quarantine. However, the impact of this price increase may differ depending on the type of passenger and the specific route.

In order to consider the potential impact of these costs on passenger volumes, we look at five example routes involving round-trips from the UK to different destinations around the world. We distinguish between three passenger types by the purposes of their travel: for business, for visiting friends and relatives (VFR), and for leisure. The routes that we consider are as follows:⁹⁸

- London–New York—as an example route for **transatlantic business travel**;
- London–Frankfurt—as an example route for **intra-Europe business travel**;
- UK–Singapore—as an example route for **UK-Asia business travel**;
- UK–Pakistan—as an example route for **VFR**;
- Manchester–Canaries—as an example route for **leisure travel**.

We model costs based on the actual travel policies in place as of 22 March 2021. The test and quarantine requirements for travellers entering each location are detailed in the table below.⁹⁹

Table 5.1 Test and quarantine requirements

Location	Test required to enter	Post-arrival requirements
1 UK	Pre-departure	Ten-day quarantine at home (or in hotel for individuals from certain countries) with tests on day two and eight. Quarantine can be ended early with a test after five days in England
2 New York	Pre-departure	Seven day quarantine at home with a test three to five days after travel, or ten day quarantine without a test
3 Frankfurt	Pre-departure	Ten-day quarantine at home that can be ended after five days with test
4 Singapore	-	21-day quarantine: 14 days at government facility, seven days at home. Three tests: at arrival, after 14 days and after 21 days
5 Pakistan	Pre-departure	Mandatory home quarantine of seven days and test on arrival
6 Canaries	Pre-departure	-

Source: Oxera and Edge Health.

Note: The test and quarantine requirements listed for locations except the UK refer to travellers entering from the UK. These restrictions are usually stricter, because the UK is considered a virus variant location. For locations outside of the UK, we assume that travellers take the optional tests to end quarantine early.

We do not estimate the non-monetary costs of testing and quarantine due to uncertainty in quantifying these impacts. For instance, even if an individual needs to quarantine upon returning from a trip, that individual may be able to work from home or use annual leave for the duration of the quarantine period. It is therefore difficult to quantify the indirect impact. For this reason, the values presented in this section can be considered as a lower bound.

In addition, we assume that all passengers arriving in the UK undertake a ten-day quarantine rather than taking an additional test on day five as part of the test to release scheme. If individuals choose to use the test to release scheme

⁹⁸ We consider these routes bi-directionally. Some of the routes have been grouped into wider areas (such as the UK) to ensure that individual airline fares are not identifiable.

⁹⁹ The restrictions listed in row one refer to travellers entering from countries that are not on the red list, so we assume that quarantine is performed at home. The restrictions in rows 2–6 refer to travellers entering from the UK. Singapore allows entry for Singaporean citizens and permanent residents only.

(i.e. take a test on day five to avoid further quarantine if they receive a negative result), they would incur the additional costs of this test, although they would have fewer days of quarantine. For the other locations considered, we assume that individuals take optional tests to be released early from quarantine.

5.2 Impact on passenger volumes

In order to determine the economic impact of testing on passengers, we consider both PCR and antigen tests. We use the following prices for PCR and antigen tests, though we note that there are a wide range of prices for these tests in each location considered.

Table 5.2 Price of PCR and antigen tests at different locations

Location	Price of PCR test (GBP)	Price of antigen test (GBP)
UK	99 for individual tests, 210 for the combined mandatory day two and day eight tests	39
New York ¹⁰⁰	0	0
Frankfurt	125	53
Singapore	107	27
Pakistan	46	10
Canaries	52	22

Source: Cost of testing in the UK is based on the tests provided by qured, which is the preferred supplier of British Airways; see also <https://qured.com/returning-to-england/> (last accessed 22 March 2021). Many sites in New York offer no-cost testing—see also: <https://www1.nyc.gov/assets/doh/downloads/pdf/covid/covid-19-travel.pdf> (last accessed 22 March 2021). Cost of testing in Frankfurt is based on tests provided at Frankfurt Airport—see also: <https://www.centogene.com/covid-19/test-centers/frankfurt-airport.html> (last accessed 22 March 2021). Cost of testing in Pakistan is based on: <https://www.geo.tv/latest/321998-is-coronavirus-testing-cheaper-in-pakistan-than-other-countries> and <https://tribune.com.pk/story/2273488/drap-okays-20-minute-covid-test-kit> (websites last accessed 22 March 2021). Cost of testing in the Canaries is based on data provided by IATA.

We consider the average fare for each of the passenger types on the five routes identified—e.g. for a business passenger on the London–New York route we use a business class fare, and for the Manchester–Canaries route we use a discount economy fare. While some travellers will take account of the entire cost of their trip (e.g. including meals) when considering the additional cost created by travel protocols, we compare the additional costs of tests to the fare in this analysis. However, in the case studies below, we incorporate the total cost of the trip by including travellers' average spend abroad.

Figure 5.2 compares the cost of the tests required for travel on the selected routes to the average fares, assuming that all tests are PCR tests or that all tests are antigen tests. As illustrated below, testing makes up a large share of the cost of flying on short-haul routes. For example, on the London–Frankfurt route, testing would increase the cost of travel by between 57% and 143% depending on whether PCR or antigen tests are used. On the Manchester–Canaries route, testing would increase the cost of travel by between 149% and 55% depending on the testing methodology used.

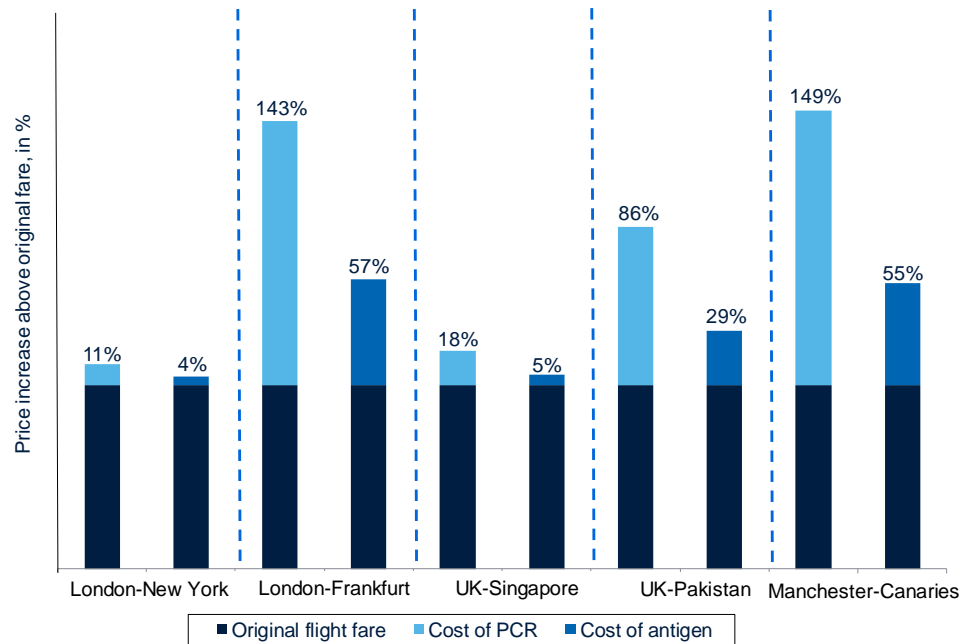
Testing also makes-up a significant proportion of the cost of flying even on some long-haul journeys, such as UK–Pakistan. The costs of testing is a lower

¹⁰⁰ Many sites in New York offer no-cost testing, see also: <https://www1.nyc.gov/assets/doh/downloads/pdf/covid/covid-19-travel.pdf> (last accessed 24 March 2021).

proportion of the fare on long-haul business routes, such as London–New York and UK–Singapore, given the higher (business class) fares on these routes.

The difference between the cost of PCR and antigen testing varies by route, but is significant for all routes considered. This highlights that moving from requiring PCR tests to allowing antigen tests—especially where several tests are required—can make a large difference for passengers.¹⁰¹

Figure 5.2 Comparing fares and testing costs, based on travel protocols in place as of March 2021



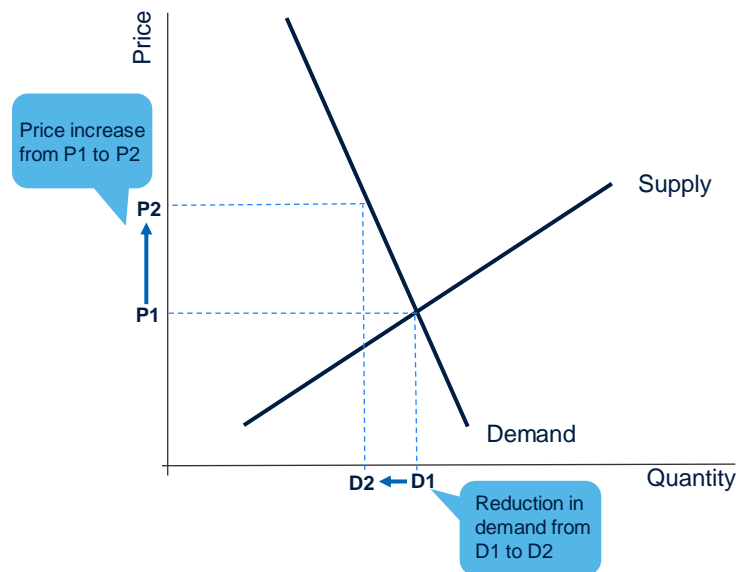
Source: Oxera and Edge Health.

Note: Flight fares include taxes. Quarantine costs are not taken into account.

As testing requirements increase the cost of international travel, it is likely that demand will be impacted. Figure 5.3 below provides a simplified illustration of this effect: as the price of a good increases (from P_1 to P_2), demand for that product decreases (from D_1 to D_2).

¹⁰¹ However, we note that antigen tests are currently not permitted for entry into a number of these jurisdictions, particularly for travellers from the UK due to concerns about Variants of Concern. Therefore, most passengers would incur the higher PCR costs in order to travel.

Figure 5.3 Decrease in demand due to price increase



Source: Oxera and Edge Health.

The amount by which demand decreases on each route depends on the price increase and the price elasticity of demand. Table 5.3 sets out relevant elasticities for each route based on a 2008 study published by IATA.¹⁰² A price elasticity of -0.7 means that a 10% increase in the price of flying results in a 7% fall in passenger demand on this route.

Table 5.3 shows the implications of PCR and antigen testing regimes on passenger volumes for passengers on particular ticket types on the five example routes. For the routes where testing leads to the greatest increase in the cost of travel—i.e. London–Frankfurt and Manchester–Canaries—demand with a PCR testing regime would decline to zero based on only considering testing costs and the fare.¹⁰³ Overall, 65% of passengers would be lost on the five example routes/ticket types assuming that all tests performed are PCR.

An antigen testing regime also leads to a reduction in demand in comparison to 2019 travel volumes. However, as antigen testing is much less expensive, the impact is considerably smaller. Only half of the travel volume on the London–Frankfurt or Manchester–Canaries route would be lost if the same number of tests are required but antigen tests are used instead of PCR tests. Across the routes/ticket types considered, approximately 30% of pre-COVID travellers would potentially be lost.

¹⁰² IATA (2008), 'IATA Economic Briefing No. 9: Air Travel Demand', April.

¹⁰³ Some essential travel, such as compassionate travel, is still likely to occur on these routes.

Table 5.3 Reduction in demand based on PCR and antigen testing regimes

Route	Cabin class considered	Elasticity	Reduction in demand with PCR regime	Reduction in demand with antigen regime
London–New York	Business class	-0.7	-8%	-3%
London–Frankfurt	Business class	-0.9	-100%	-51%
UK–Singapore	Business class	-0.5	-9%	-3%
UK–Pakistan	Discount economy class	-0.5	-43%	-15%
Manchester–Canaries	Discount economy class	-0.9	-100%	-49%

Source: Oxera and Edge Health based on IATA data.

Note: Flight fares include taxes. Quarantine costs are not taken into account.

Figure 5.2 and Table 5.3 do not account for the cost of quarantine, which can be significant. The following case studies therefore detail the full impact of testing and quarantining for travellers on three of the routes considered above. In these case studies, we compare the testing and quarantine costs to the fare as well as the entire cost of the trip. We estimate the cost of the trip using data from the ONS that shows that the average spend per visit by a UK resident overseas was £670 in 2019, and £696 for an incoming tourist (£98 per day).¹⁰⁴

5.2.1 Case study I: business traveller flying from Singapore into the UK

A traveller flying from Singapore into the UK for a five-day business trip pays an average bi-directional fare of £3,500 in business class. To enter the UK, one pre-departure test and two tests on arrival (day two and day eight), as well as a ten-day quarantine are required. If all tests need to be PCR tests, this would add over £300.¹⁰⁵ Given that this individual does not live in the UK, they will need to quarantine at a hotel at an average price of £175 per night,¹⁰⁶ adding £1,750 in costs for the quarantine period.

When returning to Singapore, the traveller needs to undergo three tests and a 21-day quarantine—14 of which need to be spent at a government facility—at a cost of £1,390.¹⁰⁷

Overall, this would double the travel cost from approximately £3,500 to £7,000 when only considering the cost of the flight and testing/quarantine. It would increase the cost of the trip by 71% when also considering the additional five-day hotel stay post-quarantine and the potential spend by the traveller in the

¹⁰⁴ ONS (2020), 'Travel trends: 2019', 22. May. See also:

<https://www.ons.gov.uk/peoplepopulationandcommunity/leisureandtourism/articles/traveltrends/2019> (last accessed 24 March 2021). We assume these figures do not include the cost of accommodation.

¹⁰⁵ Day two and day eight testing prices range from £170 to £475, for more information see <https://www.gov.uk/guidance/providers-of-day-2-and-day-8-coronavirus-testing-for-international-arrivals> (last accessed 22 March 2021). We assume the traveller incurs a cost of £220 for the two tests in the UK, and a cost of £107 for the pre-departure test in Singapore.

¹⁰⁶ The average hotel cost in London was £175 in 2016. See Statista (2020), 'Average room rate of hotels in cities in the United Kingdom (UK) 2016', 19 November.

¹⁰⁷ It is noted that only Singaporean citizens and permanent residents can enter the country from the UK as of March 2021. Cost of quarantine is set at 2,000 SGD by the government. For more information on testing and quarantine rules for international travellers, see <https://www.mfa.gov.sg/Overseas-Mission/Mumbai/Announcements/Travellers-to-bear-costs-of-COVID-19-tests-and-stay-at-Dedicated-SHN-Facilities> (last accessed 17 March 2021).

UK. Aside from the cost increase, the strict quarantine requirements in place make it unlikely that passengers would travel on this route.

5.2.2 Case study II: couple flying from the UK to Pakistan to visit family

A couple flying from the UK to Pakistan on discount economy class tickets pay an average bi-directional fare of £468 per person. To enter Pakistan, the couple needs to take a PCR test in the UK before they depart, and then a test on arrival in Pakistan for a cost of £290 in total. The couple also needs to self-isolate for seven days, but can do so at no (additional monetary) cost at home (e.g. staying with their family).

Before returning to the UK, the couple needs to take another pre-departure test as well as two tests upon arriving in the UK for a total cost of over £500. They can undergo the ten-day quarantine at their own house, which means they do not need to pay for accommodation.

In total, the testing requirements on this route increase the cost of travel, when considering only the fare and testing costs, from £940 based on the fare for two people to £1,740, a price increase of 86%. When also incorporating potential spend of the couple abroad, the cost of testing would increase the cost of the trip by 35%.¹⁰⁸

5.2.3 Case study III: family holiday to the Canary Islands

A family of four flying from Manchester to the Canary Islands pays an average fare of just over £1,000 for four discount economy class tickets. Prior to departure, the family needs to take pre-departure tests—assuming the kids are older than six, all of them need to take a test. If PCR tests are required, that will add nearly £400 in costs.

As Spain does not require international travellers to self-isolate, the family does not incur any additional cost quarantining on the Canary Islands. Before returning to Manchester, however, they each need to take a pre-departure test, as well as two PCR tests when they arrive back home. These three tests add another £1,160.

Altogether, the travel cost for the family of four more than doubles from just over £1,000 to over £2,600, a rise of about 160%. Even when considering the average spend on the total holiday of £3,950, the increase in the cost would be 32%.¹⁰⁹

5.3 Additional economic impacts

A reduction in passenger demand will lead to a loss in revenue for airlines. Demand declines more with PCR testing than with antigen testing, because the costs associated with PCR testing are higher. With a PCR testing regime, airlines could incur losses of around £335m on the five routes analysed.¹¹⁰ This amounts to 27% of total revenues of the ticket types considered on these five routes (see Table 5.3). When fewer people fly, this will also impact other parts of the aviation value chain—e.g. airports, ground-handling companies—which are not incorporated in these estimates.

¹⁰⁸ Based on spending abroad of £670 per person, or £1,340 in total.

¹⁰⁹ This includes an average spend of £670 per person and an average daily rate of hotels in Spain of £90 (see also Diaz (2020), 'Average daily rate (ADR) of hotels in Spain in August 2020, by star rating', 12 November). We assume a family of four books two hotel rooms.

¹¹⁰ This is based on the specific ticket types considered, and therefore does not account for all passengers on the route.

In addition, the aviation industry directly contributes £22bn to the UK economy and supports around half a million jobs (based on pre-pandemic figures).¹¹¹ Aviation enables tourists to reach the UK, spending a total of £28.5bn per year in the UK in pre-pandemic times.¹¹² According to the ONS, tourism as a whole contributed £145.9bn, or 7.2%, to the UK economy and directly created employment for 1.7m people in 2018.¹¹³ As a result, if there are fewer international travellers, this will have follow-on impacts for other sectors of the economy.

In addition, a share of the cost of travel is composed of government taxes (e.g. APD on UK routes), which may be lost due to the travel protocols set out above. For instance, with a PCR testing regime, the UK government could lose around 41% of total tax revenues on these routes.¹¹⁴ Given APD revenues of around £3.7bn in the pre-pandemic period (2018/2019), a similar reduction on other routes could lead to losses of around £1.5bn for the Treasury.¹¹⁵ This also equals the cost of providing an additional 38.5m antigen tests at Heathrow Airport. If antigen tests were used instead, only 17% in tax revenues would be lost.

5.4 Conclusion

There are a number of public health benefits of testing passengers before departure or on arrival, particularly for travel from certain countries. However, in designing travel protocols for international travel, it is important to consider the number/types of tests required, as well as the economic costs alongside any additional public health benefits, given the significant impacts of travel protocols on passenger volumes, the aviation sector and the wider economy. On balance, antigen testing offers a costs effective test solution that, as seen in earlier sections, provides effective risk mitigation.

¹¹¹ HM Treasury (2018), 'Aviation 2050: The future of UK aviation', December.

¹¹² Statista (2021), 'International tourist spending in the United Kingdom (UK) 2004-2021', 5 March.

¹¹³ TourismAlliance (2019), 'UK Tourism Statistics 2019'.

¹¹⁴ This is based on the specific ticket types considered, and therefore does not account for all passengers on the route.

¹¹⁵ For APD revenues for the last ten financial years, see HM Revenue & Customs (2021), 'Air Passenger Duty statistics Commentary September 2020', 25 February.

6 Conclusion

Over the past year, a number of different types of restrictions have been introduced for international travel. While testing schemes are now in place for travel to/from most jurisdictions, the particular type of testing regime varies considerably. For example, some jurisdictions require pre-departure tests at least 72 hours before departure, while others require tests on arrival in addition to/instead of pre-departure tests. There are also different requirements in terms of the type of tests accepted—e.g. PCR vs antigen tests.

As governments around the world are considering how to safely restart international travel over the coming months, it is relevant to consider the most effective testing schemes that could be put in place. While the sensitivity of tests (i.e. the ability of tests to accurately identify infected travellers) is a key element of an effective testing scheme, it is also important to take account of other aspects, such as capacity, feasibility and costs of different testing schemes.

In this report, we have undertaken a review of evidence on testing technologies for SARS-CoV-2, specifically considering their use in the context of air passenger testing.

There is a great deal of literature on different types of tests, including empirical studies on their effectiveness, and papers setting out their advantages and disadvantages. There is also an increasing amount of real-world data from instances where these tests have been used on different populations (e.g. students, air passengers, etc.). We have systematically reviewed papers focusing on real-world evidence of test performance (rather than theoretical modelling). A review of this literature indicates that while PCR tests have the highest sensitivity, there are a number of antigen tests that exhibit high specificity and sensitivity, and would therefore be able to accurately identify infected travellers. However, as there are a range of antigen tests available, it is important to ensure that there are commonly accepted standards for antigen tests.

Our economic modelling considers the effectiveness of different single testing regimes in identifying air passengers with COVID-19. It indicates that a single antigen test on departure is as effective as a ten-day quarantine regime (as is currently required in the UK), when taking account of compliance with quarantine. It also shows that antigen testing is nearly as effective as PCR testing for the different testing schemes considered (e.g. before departure, after arrival).

These results, when considered in the context of the cost of testing and the potential impact that this could have on passengers and the industry in terms of reduction in demand, indicates that single-test systems using rapid tests are best able to enable international travel to safely restart, and accommodate a rise in passenger numbers over time. They are also likely to be sufficient to reduce the risk of infection from COVID-19 from air passengers, particularly for air passengers from countries where prevalence rates are low, and as vaccinations are rolled out across countries.

A1 Literature review

Table A1.1 Comparison of academic studies evaluating real world efficacy of antigen tests, sorted by sensitivity reported

Name	Approved?	Sensitivity (%)	Specificity (%)	Population	Comment	Source (last accessed 16 March 2021)
RapiGEN	yes	28	-	Unclear	Viral load cultivated from positive cases, not study of population testing—limited comparability to other studies. Sensitivity was found to be between 11% and 47%	https://www.sciencedirect.com/science/article/abs/pii/S1386653220302420
Coris	yes	30	-	-	Highest viral load is associated with better antigen detection rates	https://www.sciencedirect.com/science/article/abs/pii/S1386653220301979
Sofia antigen	yes	41	98.4	Asymptomatic		https://www.cdc.gov/mmwr/volumes/69/wr/mm695152a3.htm
Innova lateral flow (Liverpool study)		49	99.93	Asymptomatic	Better on patients with high viral load: 66.7% sensitivity for patients with count value <25. Interestingly, PHE had found much higher sensitivity and specificity: the specificity of the test was recorded as 99.68%; the overall false positive rate was 0.32%, although this was lowered to 0.06% in a lab setting. It has an overall sensitivity of 76.8% for all PCR-positive individuals but detects over 95% of individuals with high viral loads, and there is minimal difference between the ability of the test to pick up viral antigens in symptomatic and asymptomatic individuals (see: https://www.ox.ac.uk/news/2020-11-11-oxford-university-and-phe-confirm-lateral-flow-tests-show-high-specificity-and-are , last accessed 16 March 2021)	https://www.bmj.com/content/371/bmj.m4848

Name	Approved?	Sensitivity (%)	Specificity (%)	Population	Comment	Source (last accessed 16 March 2021)
Coris	yes	50	95.8	Mixed (contact with positive person, symptoms or travel to high-risk area)		https://www.medrxiv.org/content/10.1101/2020.1.0.1.20203836v1
Coris	yes	50	100	Symptomatic		https://jcm.asm.org/content/58/8/e00977-20
Coris	yes	58	99.5	Unclear	Viral load cultivated from positive cases, not study of population testing—limited comparability	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7227790/
RapiGEN	yes	62	100	Symptomatic	Higher sensitivity on high viral load patients: 84.9%	https://www.biorxiv.org/content/10.1101/2020.05.27.119255v2
SD Biosensor	yes	62.3	-	Asymptomatic		https://www.medrxiv.org/content/10.1101/2020.1.1.23.20237198v1
Panbio Abbott	yes	66	-	Mixed		https://www.medrxiv.org/content/10.1101/2020.1.1.23.20237198v2
Bioeasy	yes	67	93.1	Mixed (contact with positive person, symptoms or travel to high-risk area)		https://www.medrxiv.org/content/10.1101/2020.1.0.1.20203836v1
SD Biosensor	yes	69	-	Symptomatic		https://www.medrxiv.org/content/10.1101/2020.1.1.23.20237198v1
Panbio Abbott	yes	73	100	Symptomatic		https://www.sciencedirect.com/science/article/pii/S2589537020304211#fig0002
Panbio Abbott	yes	74	-	Symptomatic		https://www.medrxiv.org/content/10.1101/2020.1.1.23.20237198v1
SD Biosensor	yes	77	99.3	Mixed (contact with positive person, symptoms or travel to high-risk area)		https://www.medrxiv.org/content/10.1101/2020.1.0.1.20203836v1
Sofia antigen	yes	80	98.8	Symptomatic		https://www.cdc.gov/mmwr/volumes/69/wr/mm695152a3.htm

Name	Approved?	Sensitivity (%)	Specificity (%)	Population	Comment	Source (last accessed 16 March 2021)
Espline	yes	81	100	Unclear		https://www.medrxiv.org/content/10.1101/2020.06.16.20131243v1.full.pdf
Bioeasy	yes	85	100	Symptomatic	Higher sensitivity on high viral load patients. Authors conclude: rapid antigen detection has the potential to serve as an alternative diagnostic method, especially in patients presenting with high viral loads in early phases of infection	https://www.biorxiv.org/content/10.1101/2020.05.27.119255v1
BinaxNOW	yes	89	99.9	Mixed (community setting)		https://pubmed.ncbi.nlm.nih.gov/33367619/
Bioeasy	yes	99	100	Symptomatic	93.7% of samples were from the first week after symptom onset.	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7263236/
Various (meta study)		57.6	99.5	Mixed	Meta study that found: antigen tests sensitivity varied considerably across studies (from 0% to 94%, based on eight evaluations in five studies on 943 samples). Rapid molecular assays: sensitivity showed less variation compared to antigen tests (from 68% to 100%)—average sensitivity was 95.2% (95% CI 86.7% to 98.3%) and specificity 98.9% (95% CI 97.3% to 99.5%), based on 13 evaluations in 11 studies of 2255 samples	https://pubmed.ncbi.nlm.nih.gov/32845525/#:~:text=Point%2Dof%2Dcare%20antigen%20and%20molecular%20tests%20to%20detect%20current,reducing%20household%20and%20community%20transmission

A2 Assumptions for air passenger modelling

Table A2.1 Assumptions for air passenger infectious days modelling

Model input	Description
Number of people intending to fly	Average monthly historical volumes from 2019 scaled to reflect 2020 volumes. ¹¹⁶ To reflect potential future airline volume increases as vaccinations are rolled out and protection to the domestic population increases, we present potential airline volumes 10–30% higher than they were in 2020 in section 4.3.2.
Departure countries	EU and USA
Duration of flight	Two hours for EU flights and eight hours for USA flights
Proportion of infected passengers (prevalence estimates)	Based on prevalence of the passenger's departure region (either USA or EU). 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 prevalence when the difference in prevalence between the departure and arrival locations was at its lowest, highest, and median values over the course of 2020 Underlying age/comorbidity structures and passenger demographics not considered ¹¹⁷
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) ¹¹⁸
Incubation period (i.e. time from exposure to onset of symptom)	Gamma ($\mu = 5.5$, $\sigma^2 = 6.5$) 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 ¹¹⁹

¹¹⁶ UK Civil Aviation Authority (2020), 'Airport data 2020 05', July, available at: <https://www.caa.co.uk/Data-and-analysis/UK-aviation-market/Airports/Datasets/UK-Airport-data/Airport-data-2019/> (last accessed 16 March 2021).

¹¹⁷ Russell, T. W., Golding, N., Hellewell, J., Abbott, S., Wright, L., Pearson, C. A. B., van Zandvoort, K., Jarvis, C. I., Gibbs, H., Liu, Y., Eggo, R. M., Edmunds, J. W., and Kucharski, A. J. (2020), 'Reconstructing the early global dynamics of under-ascertained COVID-19 cases and infections', *medRxiv*, available online at: <https://doi.org/10.1101/2020.07.07.20148460> (last accessed 16 March 2021).

¹¹⁸ Buitrago-Garcia, D. C., Egli-Gany, D., Counotte, M. J., Hossmann, S., Imeri, H., Ipekci, A. M., et al. (2020), 'The role of asymptomatic SARS-CoV-2 infections: rapid living systematic review and meta-analysis', *medRxiv*, available online at: <https://www.medrxiv.org/content/10.1101/2020.04.25.20079103v2> (last accessed 16 March 2021).

¹¹⁹ Lauer, S. A., Grantz, K. H., Bi, Q., Jones, F. K., Zheng, Q., Meredith, H. R., et al. (2020), 'The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application', *Annals of Internal Medicine*, **172**:9, pp. 577–82, available at: <http://dx.doi.org/10.7326/M20-0504> (last accessed 16 March 2021).

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 ($\mu = 6, \sigma^2 = 12$) Median: 5.3 days IQR: (3.5, 7.8) days 95%: (1.2, 14.4) days ¹²⁰
Symptomatic period (i.e. time after onset of symptoms until no longer symptomatic)	Gamma ($\mu = 9.1, \sigma^2 = 14.7$) Median: 8.6 days IQR: (6.3, 11.3) days 95%: (3.2, 18.0) days Derivation based on moment matching distributions ¹²¹
RT-PCR testing 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. ¹²²
RT-LAMP testing sensitivity	A scaling factor for the relative effectiveness of RT-LAMP testing (0.9) compared to RT-PCR testing is applied to the RT-PCR test sensitivity distribution. ¹²³
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 base case antigen test used in our analysis is referred to as the FDA-approved antigen test throughout the paper. It has the following reported sensitivities compared to PCR: <ul style="list-style-type: none">• pre-symptomatic: 80%;

¹²⁰ Wölfel, R., Corman, V. M., Guggemos, W., Seilmaier, M., Zange, S., Müller, M. A., et al. (2020), 'Virological assessment of hospitalised patients with COVID-2019', *Nature*, **581**:7809, pp. 465–9, available at: <http://dx.doi.org/10.1038/s41586-020-2196-x>; Byrne, A. W., McEvoy, D., Collins, A., Hunt, K., Casey, M., Barber, A., et al. (2020), 'Inferred duration of infectious period of SARS-CoV-2: rapid scoping review and analysis of available evidence for asymptomatic and symptomatic COVID-19 cases', *medRxiv*, available at: <https://www.medrxiv.org/content/10.1101/2020.04.25.20079889v1> (last accessed 16 March 2021).

¹²¹ Quilty, B. J., Clifford, S., Flasche, S., Eggo, R. M., CMMID nCoV working group (2020), 'Effectiveness of airport screening at detecting travellers infected with novel coronavirus (2019-nCoV)', *Eurosurveillance*, **25**:5, available at: <http://dx.doi.org/10.2807/1560-7917.ES.2020.25.5.2000080> (last accessed 16 March 2021); Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., et al. (2020), 'Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia', *New England Journal of Medicine*, **382**:13, pp. 1199–207, available at: <http://dx.doi.org/10.1056/NEJMoa2001316> (last accessed 16 March 2021).

¹²² See: [https://www.thelancet.com/journals/laninf/article/PIIS1473-3099\(20\)30630-7/fulltext](https://www.thelancet.com/journals/laninf/article/PIIS1473-3099(20)30630-7/fulltext) (last accessed 16 March 2021).

¹²³ Yokota, I., Shane, P. Y., Okada, K., Unoki, Y., Yang, Y., Inao, T., Sakamaki, K., Iwasaki, S., Hayasaka, K., Sugita, J., Nishida, M., Fujisawa, S. and Teshima, T. (2020), 'Mass screening of asymptomatic persons for SARS-CoV-2 using saliva', *Clinical Infectious Diseases*, ciaa1388, available at: <https://doi.org/10.1093/cid/ciaa1388> (last accessed 16 March 2021).

- 0–7 days post-symptom onset: 95%;¹²⁴
- 8+ days post-symptom onset: 80%;
- asymptomatic: 80%.

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. ¹²⁵ 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. ¹²⁶ This is based on survey evidence in the UK population from King's College London. ¹²⁷ 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. ¹²⁸ As a sensitivity analysis a syndromic screening of 70% is included, reflecting early modelling on pre-departure screening. ¹²⁹

¹²⁴ Pilarowski et al. (2020), 'Field performance and public health response using the BinaxNOWTM Rapid SARS-CoV-2 antigen detection assay during community-based testing'.

¹²⁵ ONS Survey on non-exempt passenger behaviour, available at: <https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/adhocs/12575nonexemptinternationalarrivalsselfisolationbehaviouralsurvey-pilotuk30septemberto8october2020> (last accessed 16 March 2021).

¹²⁶ Quilty, B. J., Clifford, S., Flasche, S., Eggo, R. M., CMMID nCoV working group (2020), 'Effectiveness of airport screening at detecting travellers infected with novel coronavirus (2019-nCoV)', *Eurosurveillance*, **25**:5, available at: <http://dx.doi.org/10.2807/1560-7917.ES.2020.25.5.2000080> (last accessed 16 March 2021).

¹²⁷ 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).

¹²⁸ 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).

¹²⁹ Gostic, K., Gomez, A. C., Mummah, R. O., Kucharski, A. J., Lloyd-Smith, J. O. (2020), 'Estimated effectiveness of symptom and risk screening to prevent the spread of COVID-19', *Elife*. 24 February, available at: <http://dx.doi.org/10.7554/eLife.55570> (last accessed 16 March 2021).

A3 Assumptions for UK domestic prevalence modelling

Table A3.1 Assumptions for UK domestic infectious days modelling

Model input	Description
Proportion of infected population (prevalence estimates)	The Office for National Statistics in the UK publishes weekly reports of the percent of people in the community testing positive for SARS-CoV-2. ¹³⁰ These estimates are made at the national level, which we use to calculate the UK community prevalence.
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) ¹³¹
Incubation period (i.e. time from exposure to onset of symptom)	Gamma ($\mu = 5.5$, $\sigma^2 = 6.5$) 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 ¹³²
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 ($\mu = 6$, $\sigma^2 = 12$) Median: 5.3 days IQR: (3.5, 7.8) days 95%: (1.2, 14.4) days ¹³³
Symptomatic period (i.e. time after onset of symptoms until no longer symptomatic)	Gamma ($\mu = 9.1$, $\sigma^2 = 14.7$) Median: 8.6 days IQR: (6.3, 11.3) days

¹³⁰ See: <https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/conditionsanddiseases/bulletins/coronaviruscovid19infectionsurveyypilot/previousReleases> (last accessed 16 March 2021).

¹³¹ Buitrago-Garcia, D. C., Egli-Gany, D., Counotte, M. J., Hossmann, S., Imeri, H., Ipekci, A. M., et al. (2020), 'The role of asymptomatic SARS-CoV-2 infections: rapid living systematic review and meta-analysis', *medRxiv*, available online at: <https://www.medrxiv.org/content/10.1101/2020.04.25.20079103v2> (last accessed 16 March 2021).

¹³² Lauer, S. A., Grantz, K. H., Bi, Q., Jones, F. K., Zheng, Q., Meredith, H. R., et al. (2020), 'The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application', *Annals of Internal Medicine*, **172**:9, pp. 577–82, available at: <http://dx.doi.org/10.7326/M20-0504> (last accessed 16 March 2021).

¹³³ Wölfel, R., Corman, V. M., Guggemos, W., Seilmaier, M., Zange, S., Müller, M. A. et al. (2020), 'Virological assessment of hospitalised patients with COVID-2019', *Nature*, available at: <http://dx.doi.org/10.1038/s41586-020-2196-x> (last accessed 16 March 2021); Byrne, A. W., McEvoy, D., Collins, A., Hunt, K., Casey, M., Barber, A. et al. (2020), 'Inferred duration of infectious period of SARS-CoV-2: rapid scoping review and analysis of available evidence for asymptomatic and symptomatic COVID-19 cases', *medRxiv*, available at: <https://www.medrxiv.org/content/10.1101/2020.04.25.20079889v1> (last accessed 16 March 2021).

	95%: (3.2, 18.0) days Derivation based on moment matching distributions ¹³⁴
RT-PCR test 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. ¹³⁵
Compliance with getting tested if symptomatic	Kings College London: 10.9% ¹³⁶
Compliance rate	18.2% ¹³⁷ for symptomatic individuals, evidence from King's College London.

¹³⁴ Quilty, B. J., Clifford, S., Flasche, S., Eggo, R. M., CMMID nCoV working group (2020), 'Effectiveness of airport screening at detecting travellers infected with novel coronavirus (2019-nCoV)', *Eurosurveillance*, **25**:5, available at: <http://dx.doi.org/10.2807/1560-7917.ES.2020.25.5.2000080> (last accessed 16 March 2021); Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., et al. (2020), 'Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia', *New England Journal of Medicine*, **382**:13, pp. 1199–207, available at: <http://dx.doi.org/10.1056/NEJMoa2001316> (last accessed 16 March 2021).

¹³⁵ See: [https://www.thelancet.com/journals/laninf/article/PIIS1473-3099\(20\)30630-7/fulltext](https://www.thelancet.com/journals/laninf/article/PIIS1473-3099(20)30630-7/fulltext) (last accessed 16 March 2021).

¹³⁶ Smith, L. E., Potts, H. W. W., Amlot, R., Fear, N. T., Michie, S. and Rubin, J. (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', September, available at: <https://doi.org/10.1101/2020.09.15.20191957> (last accessed 16 March 2021).

¹³⁷ Steens, A., Freiesleben de Blasio, B., Veneti R., Gimma, A., Edmunds, W. J., Van Zandvoort, K., Jarvis, C. I., Forland, F., Robberstad, B. (2020), 'Poor self-reported adherence to COVID-19-related quarantine/isolation requests', Norway, *Eurosurveillance*, **25**:37, available at: <https://doi.org/10.2807/1560-7917.ES.2020.25.37.2001607> (last accessed 16 March 2021).

A4 Relative efficacy of testing schemes: sensitivity analysis

In this section, we assess the impact of changing input assumptions on the relative efficacy of testing schemes. We vary two input parameters in the sensitivity analysis: syndromic screening efficacy and the pre-departure quarantine requirement.

The relative efficacy of testing schemes depends on input assumptions regarding syndromic screening (see Figure A4.1). If we assume (for our sensitivity analysis) that 70% of symptomatic passengers at the time of departure choose not to fly,¹³⁸ then the base case will screen a higher number of infectious days. As all of the testing scenarios are benchmarked against the base case, this in turn means that the relative efficacy of testing schemes will be lower.¹³⁹ This leads to a 5–10% reduction in the relative efficacy.¹⁴⁰

However, as evidence suggests that a relatively small proportion of individuals comply with quarantine when symptomatic, the relative efficacy values assuming syndromic screening of 18.2% are likely to be more reflective of the marginal benefit of implementing a testing scheme, particularly if governments do not want to rely on passenger compliance pre-arrival, where they have less ability to influence compliance (other than through the use of passenger declarations on arrival).

For antigen tests included in Figure A4.1, antigen test performance is similar to that of PCR and LAMP testing.¹⁴¹

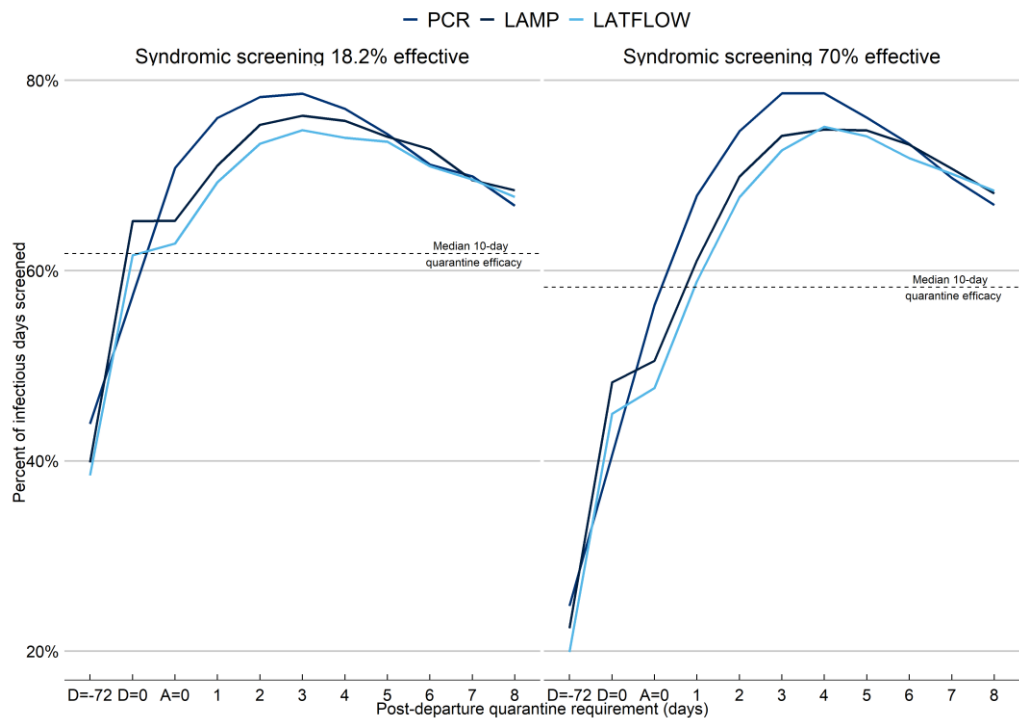
¹³⁸ Self-screening is assumed to be the major driver of pre-departure syndromic screening, as efforts to screen passengers based on symptoms have been shown to be ineffective, as outlined in the methods section.

¹³⁹ The absolute efficacy of the testing schemes in terms of the absolute infectious days screened via a combination of syndromic screening and testing will most likely be unchanged.

¹⁴⁰ This effect is lower for scenarios with longer post-arrival quarantine durations. The impact of the syndromic screening assumption is consistent across test technology types.

¹⁴¹ Two brands of antigen tests are presented in Table A4.1, which leads to a wider interquartile range for antigen testing than the other testing technologies.

Figure A4.1 Relative efficacy by test administration timing, test technology, and syndromic screening assumptions



Source: Oxera and Edge Health.

An additional pre-departure quarantine requirement increases the proportion of infectious days screened by the testing scheme—see Table A4.1 for results. Some passengers may already be practicing social distancing or quarantining before flights because they do not want to be refused boarding due to having symptoms. Thus, the performance of pre-departure testing may be between the no pre-departure quarantine results and pre-departure quarantine results presented in Table A4.1.

Table A4.1 Comparison of pre-departure testing schemes with and without a pre-departure quarantine requirement

Timing of test	PCR	LAMP	FDA-approved antigen test
Test 72 hours before departure, no pre-departure quarantine	45% (23–69%)	41% (18–63%)	38% (17–59%)
Test 72 hours before departure, pre-departure quarantine	62% (41–82%)	59% (35–81%)	58% (33–77%)

Source: Oxera and Edge Health. Assuming .182 syndromic screening. 90% confidence intervals are presented in brackets, based on the fifth and 95th percentiles of our simulation result.

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