Preprint and journal submission Wednesday 10th June

Modelling the health and economic impacts of Population-wide Testing, contact Tracing and Isolation (PTTI) strategies for COVID-19 in the UK

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Abstract

Background
The COVID-19 epidemic in the UK has resulted in over 280,000 reported cases and over 40,000 deaths as of 5th June 2020. In the context of a slower increase in reported cases and deaths associated with COVID-19 over the last few weeks compared to earlier in the epidemic, the UK is starting to relax the physical restrictions ('lockdown') that have been imposed since 23 March 2020. This has been accompanied by the announcement of a strategy to test people for infection, trace contacts of those tested positive, and isolate positive diagnoses. While such policies are expected to be impactful, there is no conclusive evidence of which approach to this is likely to achieve the most appropriate balance between benefits and costs. This study combines mathematical and economic modelling to estimate the impact, costs, feasibility, and health and economic effects of different strategies.

Methods
We provide detailed description, impact, costing, and feasibility assessment of population-scale testing, tracing, and isolation strategies (PTTI). We estimate the impact of different PTTI strategies with a deterministic mathematical model for SARS-CoV-2 transmission that accurately captures tracing and isolation of contacts of individuals exposed, infectious, and diagnosed with the virus. We combine this with an economic model to project the mortality, intensive care, hospital, and non-hospital case outcomes, costs to the UK National Health Service, reduction in GDP, and intervention costs of each strategy. Model parameters are derived from publicly available data, and the model is calibrated to reported deaths associated with COVID-19. We modelled 31 scenarios in total (Panel 2). The first 18 comprised nine with 'triggers' (labelled with the -Trig suffix) for subsequent lockdown periods (>40,000 new infections per day) and lockdown releases (<10,000 new infections per day), and nine corresponding scenarios without triggers, namely: no large-scale PTTI (scenario 1); scale-up of PTTI to testing the whole population every week, with May–July 2020 lockdown release (scenario 2b), or delayed lockdown release until scale-up complete on 31 August 2020 (scenario 2a); these two scenarios with mandatory use of face coverings (scenarios 3a and 3b); and scenarios 2a, 2b, 3a, 3b replacing untargeted PTTI with testing of symptomatic people only (scenarios 4a, 4b, 4c, 4d). The final 13 scenarios looked at: whole population weekly testing to suppress the

epidemic with lower tracing success (scenarios 3b-Trig00, 3b-Trig10, 3b-Trig20, 3b-Trig30) and switched to targeted testing after two months when it may suppress the epidemic (scenarios 3b-Trig00-2mo and 3b-Trig30-2mo), and targeted testing with lower tracing success (scenarios 4d-Trig10, 4d-Trig20, 4d-Trig30, 4d-Trig40, 4d-Trig50, 4d-Trig60, 4d-Trig70).

Findings

Given that physical distancing measures have already been relaxed in the UK, scenario 4d-Trig (targeted testing of symptomatic people only, with a mandatory face coverings policy and subsequent lockdown triggered to enable PTTI to suppress the epidemic), is a strategy that will result in the fewest deaths (~52,000) and has the lowest intervention costs (~£8bn). The additional lockdown results in total reduction in GDP of ~£503bn, less than half the cost to the economy of subsequent lockdowns triggered in a scenario without PTTI (scenario 1-Trig, ~£1180bn reduction in GDP, ~105,000 deaths). In summer months, with lower cold and flu prevalence, approximately 75,000 symptomatic people per day need to be tested for this strategy to work, assuming 64% of their contacts are effectively traced (~80% traced with 80% success) within the infectious period (most within the first two days and nearly all by seven days) and all are isolated – including those without any symptoms – for 14 days. Untargeted testing of everyone every week, if it were feasible, may work without tracing, but at a higher cost (scenario 3b-Trig00). This cost could be reduced by switching to targeted testing after the epidemic is suppressed (scenario 3b-Trig30-2mo), though we note the epidemic could be suppressed with targeted testing itself providing tracing and isolation has at least a 32% success rate (scenario 4d-Trig40).

Interpretation

PTTI strategies to suppress the COVID-19 epidemic within the context of a relaxation of lockdown will necessitate subsequent lockdowns to keep the epidemic suppressed during PTTI scale-up. Targeted testing of symptomatic people only can suppress the epidemic if accompanied by mandated use of face coverings. The feasibility of PTTI depends on sufficient capacity, capabilities, infrastructure and integrated systems to deliver it. The political and public acceptability of alternative scenarios for subsequent lockdowns needs to take account of crucial implications for employment, personal and national debt, education, population mental health and non-COVID-19 disease. Our model is able to incorporate additional scenarios as the situation evolves.

Funding

No specific funding was received in support of this study. Grant support for specific authors is listed under contributions.

Research in Context

Evidence before this study

To the best of our knowledge, this is the first detailed costing and economic evaluation of post-lockdown COVID-19 suppression scenarios for the UK. As a scoping review, we conducted title searches of PubMed and Google Scholar on 2nd June 2020 with the terms "(Econom* OR cost* OR benefit* OR "public health") AND (Covid* OR SARS-Cov-2) AND (evalu* OR interven* OR test* OR trac* OR TTI OR exit* OR strateg*)" and found 55 unique articles published in 2020, nine of which have a focus on country-level COVID-19 strategy. Four of these used modelling and explored different strategies, but none have combined impact studies with economic evaluation. While previous studies have modelled the impact of interventions on reduction of COVID-19 deaths and cases, most focus on evaluating the effect of physical distancing measures (lockdowns). Unlike previous models, our study focuses on strategies that would not require further lockdowns, and include combinations of population-scale contact tracing, early case detection, SARS-Cov-2 viral testing, isolation of cases, quarantine of contacts, and use of face coverings. Unlike previous studies, we explore a wide range of strategies. The feasibility of such strategies at population scale has been demonstrated under lockdown in Wuhan, China and Vo, Italy, and without lockdown in Taiwan, South Korea, and Vietnam. Population-scale tracing, testing, and isolation was originally proposed for the UK by Julian Peto, one of the co-authors here, and has recently been proposed for the USA by Harvard and Paul Romer.

Added value of this study

We show that a targeted population-scale testing, tracing, and isolation strategy can prevent tens of thousands of COVID-19 deaths at a low cost per death averted relative to current UK government expenditure. This can be done whilst limiting the total time under lockdown until 31 May 2022 (when there may be highly effective drugs or a vaccine available), assuming subsequent lockdowns are triggered with subsequent epidemic peaks that would occur without effective PTTI. We establish the feasibility of PTTI, including detailing what is needed to deliver it. We have also produced a software framework for implementing this class of model with interventions that is freely available (https://github.com/ptti/ptti).

Implications of all the available evidence

UK post-lockdown COVID-19 policy and planning can be informed by this research. Our model can also incorporate emerging evidence, including from pilot studies of large-scale testing and tracing in the UK, to provide ongoing support to decision-makers as the situation evolves. The software implementation of our model can be run with different parameter values and scenarios to reproduce these results, inform additional policy options in the UK, or to model policy options in other countries.

Introduction

UK policy to control the epidemic of COVID-19 disease (caused by the SARS-CoV-2 virus) has been nationwide lockdown in order to suppress the virus, reduce infection incidence, relieve pressure on hospitals and intensive care units, and limit deaths. With the UK starting to relax restrictions from early June, and some schools in England readmitting some students as the first step of reopening society, it is important to assess the best way to keep infections down and prevent subsequent epidemic waves. Mathematical models can be used to predict COVID-19 epidemic trends following relaxation of lockdown.[1,2] To date, the COVID-19 models focused on testing, tracing and isolation to keep the epidemic suppressed have considered the topic on its own. In this paper, we combine a model of population-wide testing, tracing, and isolation (PTTI) with an economic model to understand the effects of different PTTI and lockdown scenarios on COVID-19 health outcomes and the economy.

Recent estimates suggest that only 6.8% of the population of England (95% confidence interval [CI]: 5.2% to 8.6%) had been infected with SARS-CoV-2 as of 24 May 2020,[3] with significant regional and demographic variation. This level of presumed immunity is a long way from the roughly 60% required for herd immunity without "overshoot".[4] Overshoot involves exposing more people to the disease than is needed for herd immunity, and could increase the proportion to around 80% depending on the number of active cases[5] as the threshold is approached. Consequently, if we consider only the binary choice of lockdown or remaining open, we are likely to need lockdown for three of every four months[2,6] (or four of every six months)[2,6] until there is a vaccine to safely induce herd immunity, or highly effective drugs to prevent most deaths. Without implementing effective provision of testing, contact tracing, and isolation, in conjunction with other measures, the UK may be at risk of either spending two thirds to three quarters of time locked down, or experiencing an uncontrolled epidemic with between 250,000 and 550,000 deaths.[1]

This paper combines a mathematical model of the epidemic, including testing, contact tracing, and isolation and distancing measures, with an economic model to gauge the cost of the epidemic itself and the interventions intended to suppress it. We use this combined model to explore 31 different PTTI scenarios and identify the optimal strategy to safely reopen the UK economy whilst protecting the public from further COVID-19 infections. We consider a range of scenarios including weekly saliva testing for active infection (i.e. tests for the presence of SARS-CoV-2), and isolation of infected individuals and all of their contacts for 14 days to prevent transmission. We examine both the effects and the costs of combinations of various strategies, including targeted testing of symptomatic people only as well as regular testing of a proportion of all people, with or without contact tracing and the use of face coverings.

Weekly testing of the population was originally proposed for the UK by Julian Peto on 22 March 2020[7] and further detailed in a letter to the UK government on 10th April 2020.[8] Similar population-wide testing strategies have been proposed for the USA by a Harvard-led group and Paul Romer.[9,10] Such strategies require rapid mobilisation of the necessary expertise and resources, and implementation on an unprecedented scale throughout the country. If a high proportion of the population can be covered by sufficiently effective weekly home-based testing, then the epidemic can be suppressed, and lockdown safely lifted. With lower proportions of the population tested, tracing a high proportion of the contacts of diagnosed infected people quickly, together with isolation of these contacts for 14 symptom-free days, might ensure the epidemic is suppressed. We model health and some of the economic effects of these scenarios.

In this paper, we examine the effects of changing policies through interventions and gradually building the required capacity for testing and tracing, which has not been examined before. We detail the resources required for the PTTI interventions, including the coverages required to end the COVID-19 epidemic in the UK and keep the virus suppressed until there is a vaccine or highly effective treatment. We compare this to alternatives of an unmitigated epidemic, and intermittent lockdown triggered by resurgence of infection, without PTTI. In order to identify potentially feasible PTTI approaches, we consider cases where outbreaks have been successfully suppressed using similar strategies, albeit in diverse socio-cultural and political environments (Panel 1).

Panel 1: Evidence of successful implementation of population-scale testing, tracing and isolation strategies

Here, we summarise a number of case studies demonstrating successful approaches to suppressing COVID-19 outbreaks at the city/country level. Whilst all involve widespread use of testing, tracing and isolation, each case emphasises different aspects of PTTI strategy: large scale clinical screening (Wuhan), contact tracing (South Korea, Vietnam, Taiwan), and testing (Vo).

Wuhan, China - Wuhan, the epicentre of the global outbreak, trialed a number of control approaches. The city was quarantined on 23 January 2020, with restrictions relaxed on 8 April[11]. Testing capacity and accuracy was limited at first, so clinical case identification was heavily relied upon, with all nine million city residents screened for fever between 17 and 19 February in an operation involving 6,800 local security personnel and 14,900 local officials. Potential cases were divided into different groups: those with fever were hospitalised and tested; their close contacts were isolated in hotels, with their temperatures checked twice daily; and those testing positive were admitted to specialist COVID-19 hospitals. These measures rapidly curtailed the spread of the virus, reducing the reproduction number (R) to 0.3[12] and suppressing the epidemic to negligible levels within a month. Wuhan had another city wide testing with a total of nine million people tested between 14 and 24 May. This identified zero symptomatic cases, and only 300 non-symptomatic infected cases, and all of those have been isolated[11]. Life is getting back to normal in Wuhan – though primary schools are not yet open, university students have the option of returning to campus.

South Korea - South Korean contact tracers make widespread use of technology, using data from GPS, credit/debit cards, gyms, and public transport, as well as CCTV and interviews.[13] All traced contacts are tested, and positive cases are quarantined. Information on the movement of cases is made public, allowing citizens to match the data with their own location history and get tested if they may have been exposed. South Korea approved special legislation after the 2015 MERS outbreak to allow all of this.[14]

Vietnam - With experience of SARS-1, Vietnam reacted very quickly to the emerging pandemic. Travel restrictions and quarantine for incoming visitors were introduced in late January, and compulsory mask wearing from 16 March.[15] Contact tracing, testing, and isolation has been key to containment, with a four-level system in place:[16] (1) confirmed cases and their direct contacts (isolation/hospital treatment); (2) close contacts with 1 (quarantine in dedicated facilities); (3) close contacts with 2 (self-quarantine at home); (4) lockdown of the area where the patient lives. Extensive testing – using home-grown testing capacity[17] – has been conducted throughout, with the ratio of tests to positive cases standing at 800:1 as of 1 May. This is the highest such ratio in the world, with a ~30:1 ratio being a *de facto* threshold signalling adequate containment.[13] As of 7th June, there have been 329 documented COVID-19 cases in Vietnam, with only 67 cases recorded in the preceding eight weeks,[18] and zero recorded COVID-19 deaths.[18]

Taiwan - With close proximity and many ties to China, Taiwan was expected to suffer a massive outbreak. However, it has kept its figures low. Having previously dealt with SARS-1, the Taiwanese CDC exercised its broad powers and was quick to implement control measures: over 100 measures were already set in place before March,[19] including border controls and travel restrictions, the centralised management of high levels of mask production relative to population size (production was ramped up to 10 million per day by the end of March[19]), testing all people with recent flu-like symptoms, and enforcement of quarantine via the monitoring of phone signals. Standard human contact tracing techniques have been used; but the connection of travel and healthcare databases has allowed healthcare professionals to identify those at higher risk of being infected.[19]

Vo, Italy - Following Italy's first COVID-19 death on 21 February, the town of 3,400 was locked down for 14 days. The vast majority of the town's population was tested both at the start and at the end of the lockdown. Prevalence of infection dropped from 2.6% to 1.2% during this time (with only 0.3% infected during the two weeks of lockdown).[20] Contact tracing and transmission chain reconstruction were used to determine that the majority of transmission during lockdown resulted from asymptomatic household members.[20] This was minimised with the quarantining of those testing positive, and the epidemic was halted in 14 days.[21]

Ghana - Many in the global health community feared that African countries would be most severely hit by COVID-19, due to their weaker health systems and lower levels of economic development. However, many places have fared relatively well. Ghana in particular has been

highlighted as a success, with a total of ~10,000 confirmed cases and 44 deaths in a population of over 31 million.[22,23] Although it did implement a 21-day lockdown, its success has been partly attributed to acting quickly to mobilise a local test, track and trace programme, combining strict adherence to WHO guidelines alongside local innovation, including a real-time covid tracker, labelling of regional hotspots across the country to develop local knowledge of their pandemic, a rapid testing kit, and utilisation of drones to deliver tests in rural areas.[24]

Methods

Mathematical model for transmission of SARS-CoV-2

We model the spread of COVID-19 in the UK using a novel SEIR-TTI technique described separately.[25] SEIR-TTI extends the classic SEIR cohorts of susceptible (S), exposed to the virus but not infectious (E), infected and infectious (I), and removed (R) populations individuals with unconfined and isolated subpopulations. The removed cohort includes populations recovered from infection, hospitalised with infection, and deceased from infection. The relative proportions of the removed subpopulations are derived from existing literature, described in the economic model section below. We use a careful probabilistic argument to account for contact tracing; we do not simply assume that the isolated people are a proportion of those exposed to the virus, but compute the rate of isolation for all compartments.[25] This produces a realistic representation of the effect of isolating susceptible, exposed, and infectious individuals on disease propagation, and of unnecessary isolation of recovered individuals on costs.

The SEIR-TTI is shown schematically in Figure S1. The possible transitions between cohorts are indicated with arrows. The overall progression is from susceptible (S), to exposed (E), to infectious (I) and finally to removed (R) states. Within each of these states, an individual can be unconfined or isolated. Infectious (I) individuals who are unconfined may be tested and become isolated. An individual in any state that is traced is isolated. Once isolated, individuals remain so for 14 days. Susceptible (S) isolated individuals cannot become infected due to their isolation, and return to the unconfined state after a 14 day delay. Exposed (E) and infectious individuals (I) do not return directly to the unconfined state and first progress to removed (R). Removed (R) and isolated individuals return, as with susceptible (S) individuals, to an unconfined state once 14 days has elapsed. Tracing is described by a rate of tracing and a probability of success.

Our model incorporates interventions and triggers. An intervention changes a model parameter at a defined time. The principal parameters that are changed are the contact rate, representing differing regimes of social distancing or lock-downs, and the testing and tracing rates, representing

building up capacity. A trigger changes a parameter when a condition is met. The trigger conditions that we use are the number of infections passing a set threshold. We use different thresholds according to whether the number of infections is increasing or decreasing to avoid rapidly oscillating between distancing regimes.

We calibrate the model by matching the number of model-projected deaths to the reported UK deaths associated with COVID-19 up to 20 May 2020. We assume an infection fatality rate (IFR) of 1.0% and a lag from infection to death of 18 days. We allow the daily transmission rates in the time intervals separated by known lockdown times (23 March and 16 May) to vary freely, and minimise the difference between the projected and reported death timeseries. In this way we estimate the daily transmission rates during each time period. We then use contact rates from the literature to determine the infection probability per contact. Further details are provided in the supplementary material.

The software framework that we have developed for implementing this kind of model, the model itself, and the specification and resulting data for all scenarios described below is freely available at https://github.com/ptti/ptti.

Modelled Scenarios

To account for different policy variations, we modelled 31 scenarios in total (Panel 2). The first 18 were decided *a priori*: nine with and nine without triggers for subsequent lockdown periods and lockdown releases. The nine core scenarios are: the baseline with no testing and tracing (scenario 1); scale-up of testing to the whole population every week, with tracing, with current lockdown release (scenario 2b) and delayed lockdown release until scale-up complete (scenario 2a); these two scenarios with mandatory use of face coverings (scenarios 3a and 3b); and the previous four scenarios replacing untargeted population-scale testing with testing of symptomatic people only and tracing (scenarios 4a, 4b, 4c, 4d). The final 13 scenarios were run following discussion of the findings from the first 18 scenarios to explore emerging policy questions: whether testing the whole population every week can work to suppress the epidemic with lower tracing success (scenarios 3b-Trig00, 3b-Trig10, 3b-Trig20, 3b-Trig30) and can be switched to targeted testing after two months when it may suppress the epidemic (scenarios 3b-Trig00-2mo and 3b-Trig30-2mo) and whether targeted testing can work to suppress the epidemic with lower tracing success (scenarios 4d-Trig10, 4d-Trig20, 4d-Trig30, 4d-Trig40, 4d-Trig50, 4d-Trig60, 4d-Trig70)

Face coverings[26,27] were assumed to reduce βby 30%. This is based on an estimated 60% effectiveness of face coverings in reducing transmission[28] and a conservative assumption that they would only be worn 50% of the time,[29] i.e. for 50% of the contacts *c* occurring in the modelled scenario trajectories.

All scenarios were run, from the onset of the pandemic, in our model assumed in December 2019, through lockdown on 23 March and until 31 May 2022. Scenarios with lockdown and release triggers diverge after 23 March when thresholds for triggers are met (<10,000 cases per day to release, and >40,000 cases per day to lock down again). Scenarios without lockdown and release triggers diverge from 13 May when different interventions are set (Panel 1; see scenario .yaml files here for full details). Lockdown release triggers are set for lockdown release to: *c* = 80% of pre-pandemic contacts after lockdown release (this is the same value for c as at the end of phased lockdown release).

Panel 2: Modelled scenarios

Scenario	description	date	1/θ	χ	η	β	c0=11
Base part	Baseline trajectory to date, common to all scenarios. 18th December 2019 chosen as seeding date in line with model fitting and new report of potential first case in France from 27th Dec, infected between 14-22nd Dec and likely similar first importation to the UK. 16th March 2020, first weak measures announced to slow spread. 23rd March lockdown ordered.	18-Dec-19	0	0	0	0.0425	1
		16-Mar-20	0	0	0	0.0425	0.7
		23-Mar-20	0	0	0	0.0425	0.3
1	**Phased lockdown release, no testing and tracing.** Lockdown lifted in a phased way as per UK government COVID-19 recovery strategy (11th	13-May-20	-	0	0	0.0425	0.4
		01-Jun-20	-	0	0	0.0425	0.6

	May): those who can't work from home encouraged back to work from 13th May, some schools may open 1st June, some entertainment venues may open 4th July (the latter both subject to estimates of infections circulating and R).	04-Jul-20	-	0	0	0.0425	0.8
2a	**Weekly testing of 80% of people, contact tracing of 80% of positives within one day, with 80% of contacts traced per case while remaining in lockdown until testing scale-up completed on 31st August**. Continue lockdown from 23rd March with testing, tracing and isolation scaled up. Then relax lockdown from 31st August 2020.	18-May-20	678	0.8	0.8	0.0425	0.3
		01-Jun-20	226	0.8	0.8	0.0425	0.3
		29-Jun-20	75.3	0.8	0.8	0.0425	0.3
		27-Jul-20	22.6	0.8	0.8	0.0425	0.3
		31-Aug-20	7	0.8	0.8	0.0425	7
		28-Sep-20	7	0.8	0.8	0.0425	9
		26-Oct-20	7	0.8	0.8	0.0425	11
2b	**Weekly testing of 80% of people, contact tracing of 80% of positives within one day, with 80% of contacts traced per case - scale up during phased lockdown release.** As Scenario 1 but add contact tracing and testing, scaled up to final 80% values as per dates given (assume scale-up possible	18-May-20	678	0.8	0.8	0.0425	0.4
		01-Jun-20	226	0.8	0.8	0.0425	0.6
		29-Jun-20	75.3	0.8	0.8	0.0425	0.6
		27-Jul-20	22.6	0.8	0.8	0.0425	0.8
		31-Aug-20	7	0.8	0.8	0.0425	0.8

	by end of August).		
3a	**Cloth face coverings added to Scenario 2a**		0.02975
3b	**Cloth face coverings added to Scenario 2b**		0.02975
4a-4d	**Clinical case identification.** As scenarios 2a, 2b, 3a, 3b but with targeted testing symptomatic cases identified clinically.	Parameters the same as 2a, 2b, 3a, 3b but with targeted testing from the pool of those identified clinically (by bespoke clinical reporting system) as explained in the footnote[1]. Prevalence of those symptomatic with colds or flu is varied throughout the year. A proportion of those symptomatic with cold, flu or COVID-19 (assumed not distinguishable from each other via clinical case identification) are tested each day, with testing only of newly symptomatic (divide by 7 day duration of illness) so as to not test the same person more than once in the same illness episode	
1-Trig – 4d-Trig	**Lockdown and Lockdown Release**	Lockdown release is to c = c0 * 0.8 (80% of	

[1] The testing rate is calculated as follows. Let the base rate of testing in the population be θ_0. This must reflect all of those who are tested due to having symptoms, both from the cold or flu and from COVID-19. Let p_f be the prevalence of the cold and flu, t be the duration of symptoms and k_t be the rate of testing. Therefore the rate at which individuals are tested due to cold or flu symptoms is $\theta_0 = p_f k_t / t$. This rate impacts the costs and if cold and flu is more prevalent than COVID-19 will mostly consist of negative results. Now let the rate of testing those suffering from COVID-19 be θ_I. Since only those who are symptomatic are tested and we take the duration of symptoms to be the same, $\theta_I = s\, k_t / t$, where s is the rate of symptomaticity. Because a symptomatic individual suffering from COVID-19 may be tested for either reason, the rate of testing of those individuals used by the model for isolation and causing contact tracing is $\theta = \theta_0 + \theta_I - \theta_0\theta_I$ where the third term corrects for double counting and follows from the inclusion-exclusion principle.

	Triggers. As scenarios 1, 2a, 2b, 3a, 3b, pre-pandemic contacts) after lockdown release. 4a, 4b, 4c, 4d, but instead of phased lockdown release, Lockdown released when <10,000 cases and Lockdown triggered when >40,000 cases.
3b-Trig00, 3b-Trig10, 3b-Trig20, 3b-Trig30	**Testing everyone but with lower success of tracing.** As scenario 3b-Trig, though with lower success of tracing , eta (00=0%, 10=10%, 20=20%, 30=30%), at the same rate of tracing (chi=0.8). This is to contrast testing everyone (untargeted testing) with targeted testing of symptomatic people only - which needs higher levels of tracing to suppress the epidemic (40% and above)
3b-Trig00-2mo, 3b-Trig00-2mo	**Testing everyone but with switch to targeted testing and tracing after epidemic suppression.** As scenarios 3b-Trig00 and 3b-Trig30 but with 2 months of testing everyone every week to suppress the epidemic (from 31st August to 31st October 2020) then switching to targeted testing same as 4d-Trig from 1st November 2020
4d-Trig10, 4d-Trig20, 4d-Trig30, 4d-Trig40, 4d-Trig50, 4d-Trig60, 4d-Trig70	**Targeted testing with lower tracing success.** As scenario 4d-Trig though with lower lower success of tracing , eta (00=0%, 10=10%, 20=20%, 30=30%, 40=40%, 50=50%, 60=60%, 70=70%), at the same rate of tracing (chi=0.8).

β = transmission rate per contact

θ = Testing rate per person per day i.e. testing each person every 1/Theta days

c0=11 average contacts per day pre-pandemic. The numbers in this column are the proportion of pre-pandemic contacts that occur (0.3 is lockdown)

χ= Tracing rate per day

η= Proportion of people traced successfully traced and isolated

With χ=0.8 and η=0.8 that means 80% of contacts are traced and 80% of those are traced on the first day (64%) and the remaining 16% are traced at the beginning of the second day (i.e. 80% of contacts are traced within 1.25 days). We assume this is possible with a team of tracers working on each new case every day (supplemented with mobile phone apps)

Economic model

We employ a cost–consequence analysis,[30] and methods consistent with an impact inventory,[31] to compare our 31scenarios. We compare scenarios on four measures – deaths, National Health Service (NHS) costs, reduction in GDP, and direct intervention costs – by 31 May 2022. Deaths are calculated directly by multiplying the model-projected number of infections by the infection fatality rate (IFR). NHS costs are divided into hospital and intensive care unit (ICU) costs. reduction in GDP of the pandemic and lockdown measures are calculated by relating GDP to the model parameter *c* (contacts per day) as a proxy for economic activity, for every day of the model scenario trajectory. Intervention costs comprise contact tracing costs and testing costs and are comprised of start-up and recurring costs and are blocked into 3 month and 6 month periods for tracing and testing respectively, based on the maximum number of infections needing tracing and testing in those periods. Details of how we derive all of these costs are provided in the supplementary material. Potential health and social costs of lockdown that are not included in our economic model are also detailed in the supplementary material (Table S3). We note that, as with the mathematical model, there is a level of uncertainty in the parameters used for the economic model, and we have these as modelling assumptions in absence of precise data.

Realising Resources Required for PTTI

The budget for the PTTI strategy is shown in supplementary material Table S2. There are three principal components, which we also explain in detailed narratives in the supplementary material: (1) contact tracing using a network of public health community officers, mobile phone apps, and supervisors; (2) home-based saliva testing for active SARS-CoV-2 infection; and (3) follow-up and isolation of infected individuals and households. As per the economic model, total costs are variable depending on policy scenario and case numbers.

Results

Table 1 shows the results of all 31 scenarios and supplementary material Tables S5–S8 compare scenario results. All scenario trajectories are plotted in six-panel figures with scenario 4d-Trig shown in Figure 1 and the rest shown in the supplementary material (also available as PDF files in our Github repository). Figure 2 visually summarises the health and economic outcomes for seven key scenarios – the goal is for all bars (deaths, NHS costs – not visible as relatively small (Table 3) – reduction in GDP, and intervention i.e. tracing and testing costs) to be as small as possible.

Given that physical distancing restrictions have been relaxed in the UK, scenario 4d-Trig (targeted testing of symptomatic people only, with a mandatory face coverings policy resulting in 50% of the population wearing them, and subsequent lockdown triggered to enable TTI to suppress the epidemic) is the strategy which will result in the fewest deaths (~52,000), and lowest intervention costs (~£8bn). The additional lockdown results in total reduction in GDP of ~£503bn, less than half the cost to the economy of subsequent lockdowns triggered in a scenario without PTTI (scenario 1-Trig, ~£1180bn reduction in GDP, ~105,000 deaths). Had the initial lockdown been extended until 31st August 2020, scenario 4c (targeted testing of symptomatic people only, with a mandatory face coverings policy, and a longer initial lockdown whilst TTI is scaled up) would have resulted in slightly fewer deaths (~51,000), similar intervention costs (~£8bn) as scenario 4dTrig, and slightly greater reduction in GDP (~£575bn).

With tracing success (*eta*) as low as 40% we estimate that targeted testing still works to suppress the epidemic (scenario 4d-Trig40, Figure 2, Table 1) though with ~6,000 more deaths (~58,000) and higher cases leading to slightly longer lockdown (~£506bn reduction in GDP) and higher intervention costs (~8.5bn). With 30% traced (scenario 4d-Trig30) there were ~77,000 deaths (~25,000 more); with 20% traced two additional lockdowns were triggered (Figure S26); and with 10% traced three more additional lockdowns were triggered (Figure S25), all with associated reduction in GDP (Table 1).

Testing everyone every week, if feasible, can work with lower tracing success as low as 0% i.e. no tracing (scenario 3b-Trig00, Table 1) and after it has suppressed the epidemic with reduced costs by switching to targeted testing to maintain epidemic suppression, but only with 30% tracing success not lower (scenario 3b-Trig30-2mo, ~55,000 deaths, ~£520bn reduction in GDP, ~£8bn intervention costs), assuming that targeted testing then has higher tracing success: as high as that in 4d-Trig.

Targeted testing of symptomatic people will require testing up to 3.2% of the population every week in winter (80% of the estimated 4% of the population who have Covid or cold or flu symptoms at their peak in winter[32]). This means testing ~300,000 people a day, up from the estimated ~50,000 currently being tested.[33] Because the prevalence of cold, flu, and COVID-19 symptoms combined may be closer to 1% in June and July,[32] only ~75,000 people per day may need testing to start with under the targeted TTI strategies (e.g. scenario 4b-Trig).

Scenario 1 with phased lockdown release from 13 May through 4 July and no testing or tracing results in an unmitigated epidemic with ~600,000 deaths and reduction in GDP of £447bn. With lockdown triggers added the deaths are reduced to around 105,000, with a ~£1,180bn reduction in GDP. We used these two scenarios as the main counterfactuals for comparing the PTTI strategies to (supplementary material Table S5).

Scaling up testing and tracing during lockdown release (scenario 2b) does not bring the epidemic under control and results in impossible tracing requirements (a peak of 7 million traces a day in September 2020) and total intervention costs of £735bn. With lockdown triggers (scenario 2b-Trig) to prevent the epidemic from getting out of control, tracing and testing requirements are manageable and the intervention averts an estimated ~38,000 deaths relative to no testing and tracing, also with lockdown triggers (scenario 1-Trig). A longer initial lockdown period during scale up of testing and tracing to 31st August 2020 (scenario 2a) has very similar results to adding the lockdown triggers (scenario 2b-Trig; Table 3). Adding mandatory face coverings (scenarios 3a, 3a-Trig, 3b-Trig) saves an additional ~14,000 lives and saves around £5bn in intervention costs as less testing and tracing is required given fewer cases. Targeted testing of symptomatic cases only and tracing, with face coverings, with a longer initial lockdown during scale-up (scenarios 4c, 4c-Trig) can be as effective as weekly untargeted testing of everyone under the same conditions (scenarios 3a, 3a-Trig; Table 3).

When testing is scaled up to testing everyone every week from 31 August 2020, total testing costs by 31 May 2022 are ~£31bn–36bn (scenarios 2a –3b-Trig, Table 1 middle section). These scenarios have lower tracing costs (~£8bn for 2a, 2a-Trig, 2b-Trig; and ~£3bn for scenarios with face coverings 3a, 3a-Trig, 3b-Trig) except for when the epidemic is not suppressed and runs out of control due to scale-up happening during lockdown release (scenarios 2b and 3b; see trajectories in supplementary material Figures S5 and S9), in which case tracing costs also become too large (~£707bn and ~£149bn respectively). In reality these costs will not be met, especially given they will not result in the epidemic being controlled – only additional lockdown enables that for these scenarios (2b-Trig and 3b-Trig respectively, where lockdown is triggered when new cases increase to >40,000 per day).

With testing of symptomatic people only testing costs are contained to around ~£700m (scenarios 4a–4d-Trig, Table 1 bottom two sections). Tracing costs also depend on epidemic control or suppression and are very high when the targeted testing and tracing is unable to keep the epidemic suppressed and there are subsequent epidemic peaks (scenario 4a: ~£59bn, ~187,000 deaths; scenario 4b: ~£323bn, 283,000 deaths; scenario 4d: ~£59bn, ~108,000 deaths) and much lower when the epidemic is suppressed: ~£7bn–£12bn, scenarios 4a-Trig, 4b-Trig, 4c, 4c-Trig, 4d-Trig (Table 1). All of these scenarios involve subsequent triggering of lockdown to control the epidemic when new cases increase to >40,000 per day, except scenario 4c, which has a longer initial lockdown and the face coverings policy whilst the targeted testing is scaled up. These results highlight the trade-offs between longer lockdown, subsequently triggered lockdown, targeted and untargeted testing. Further details can be found in the supplementary material.

Table 1 Scenario results

To 31st May 2022	Scenario 1	Scenario 1-Trig
Deaths	601,133	104,753
ICU cases	139,044	24,230
Hospital (non-ICU) cases	787,915	137,301
Non-hospital cases	58,585,218	10,208,984
NHS costs (£M)	4,409	768
reduction in GDP (£M)	446,843	1,180,436
Public Health costs (£M)	0	0
of which: Testing total costs (£M)	0	0
Tracing total costs (£M)	0	0

Key:

Lockdown triggers

Longer initial lockdown

face coverings

targeted testing (symptomatics only)

lower success of tracing , *eta* (00=0%, 10=10%, 20=20%, 30=30%, 40=40%, 50=50%, 60=60%, 70=70%, default is 80%)

2mo= 2 months of testing everyone every week to suppress the epidemic then switching to targeted testing same as 4d-Trig

	Scenario 2a	**Scenario 2a-Trig**	Scenario 2b	Scenario 2b-Trig	**Scenario 3a**	**Scenario 3a-Trig**	Scenario 3b	Scenario 3b-Trig
Deaths	**66,901**	**66,911**	349,777	66,911	**52,963**	**52,962**	141,542	53,159
ICU cases	**15,474**	**15,477**	80,904	15,477	**12,251**	**12,250**	32,739	12,296
Hospital (non-ICU) cases	**87,689**	**87,701**	458,458	87,701	**69,420**	**69,418**	185,522	69,677
Non-hospital cases	**6,520,074**	**6,520,976**	34,088,536	6,520,976	**5,161,691**	**5,161,524**	13,794,439	5,180,812
NHS costs (£M)	**491**	**491**	2,565	491	**388**	**388**	1,038	390
reduction in GDP (£M)	**574,386**	**550,471**	446,843	550,471	**574,386**	**1,244,650**	446,843	516,150
Public Health costs (£M)	**36,152**	**36,167**	734,889	36,167	**31,172**	**31,172**	177,478	31,196
of which: Testing total costs (£M)	**28,252**	**28,251**	27,807	28,251	**28,260**	**28,260**	28,016	28,258
Tracing total costs (£M)	**7,901**	**7,916**	707,082	7,916	**2,913**	**2,912**	149,462	2,938

	Scenario 3b-Trig00	**Scenario 3b-Trig10**	Scenario 3b-Trig20	Scenario 3b-Trig30	**Scenario 3b-Trig00-2mo**	**Scenario 3b-Trig30-2mo**	Scenario 3b-Trig00	Scenario 3b-Trig10
Deaths	**54,722**	**54,169**	53,895	53,713	**69,835**	**54,998**	54,722	54,169
ICU cases	**12,657**	**12,529**	12,466	12,424	**16,153**	**12,721**	12,657	12,529
Hospital (non-ICU) cases	**71,725**	**71,000**	70,641	70,402	**91,535**	**72,087**	71,725	71,000
Non-hospital cases	**5,333,111**	**5,279,178**	5,252,457	5,234,739	**6,806,023**	**5,359,999**	5,333,111	5,279,178
NHS costs (£M)	**401**	**397**	395	394	**512**	**403**	401	397
reduction in GDP (£M)	**523,900**	**522,793**	521,686	520,579	**630,186**	**520,579**	523,900	522,793
Public Health costs (£M)	**32,235**	**31,768**	31,397	31,344	**16,781**	**7,635**	32,235	31,768
of which: Testing total costs (£M)	**28,261**	**28,260**	28,259	28,259	**4,389**	**4,381**	28,261	28,260

Tracing total costs (£M)	**3,974**	**3,508**	3,138	3,086	**12,392**	**3,254**	3,974	3,508
	Scenario 4a	***Scenario 4a-Trig***	*Scenario 4b*	*Scenario 4b-Trig*	***Scenario 4c***	***Scenario 4c-Trig***	*Scenario 4d*	*Scenario 4d-Trig*
Deaths	***186,785***	***60,403***	*282,853*	*76,961*	***51,242***	***51,239***	*108,287*	*51,897*
ICU cases	***43,204***	***13,971***	*65,425*	*17,801*	***11,852***	***11,852***	*25,047*	*12,004*
Hospital (non-ICU) cases	***244,822***	***79,171***	*370,740*	*100,874*	***67,163***	***67,160***	*141,934*	*68,022*
Non-hospital cases	***18,203,674***	***5,886,723***	*27,566,296*	*7,500,445*	***4,993,900***	***4,993,641***	*10,553,436*	*5,057,765*
NHS costs (£M)	***1,370***	***443***	*2,075*	*564*	***376***	***376***	*794*	*381*
reduction in GDP (£M)	***574,386***	***1,244,650***	*446,843*	*656,757*	***574,386***	***1,244,650***	*446,843*	*502,864*
Public Health costs (£M)	***59,887***	***10,408***	*323,526*	*13,011*	***7,918***	***7,918***	*59,401*	*7,995*
of which: Testing total costs (£M)	***700***	***710***	*714*	*708*	***700***	***700***	*709*	*709*
Tracing total costs (£M)	***59,187***	***9,698***	*322,812*	*12,302*	***7,218***	***7,218***	*58,693*	*7,287*
	Scenario 4d-Trig10	***Scenario 4d-Trig20***	*Scenario 4d-Trig30*	*Scenario 4d-Trig40*	***Scenario 4d-Trig50***	***Scenario 4d-Trig60***	*Scenario 4d-Trig70*	*Scenario 4d-Trig10*
Deaths	***69,581***	***68,319***	*76,648*	*58,336*	***54,056***	***52,823***	*52,253*	*69,581*
ICU cases	***16,094***	***15,802***	*17,729*	*13,493*	***12,503***	***12,218***	*12,086*	*16,094*
Hospital (non-ICU) cases	***91,201***	***89,547***	*100,464*	*76,462*	***70,852***	***69,236***	*68,489*	*91,201*
Non-hospital cases	***6,781,244***	***6,658,248***	*7,469,970*	*5,685,311*	***5,268,178***	***5,148,032***	*5,092,454*	*6,781,244*
NHS costs (£M)	***510***	***501***	*562*	*428*	***396***	***387***	*383*	*510*
reduction in GDP (£M)	***599,186***	***567,079***	*509,507*	*507,293*	***506,186***	***505,079***	*503,971*	*599,186*
Public Health costs (£M)	***12,109***	***11,328***	*11,546*	*9,114*	***8,549***	***8,307***	*8,139*	*12,109*
of which: Testing total costs (£M)	***715***	***710***	*709*	*709*	***709***	***709***	*709*	*715*
Tracing total costs (£M)	***11,394***	***10,619***	*10,837*	*8,405*	***7,841***	***7,599***	*7,430*	*11,394*

Figure 1 Trajectories for scenario 4d-Trig: targeted testing, face coverings, subsequently triggered lockdown. Top-left panel shows cumulative deaths from COVID-19 and the prevalence of hospitalised and intensive care unit (ICU) COVID-19 cases over time from 1 January 2020 to 31 May 2022. The dashed horizontal line denotes ICU 'surge' capacity of 8,000 beds. Top-right panel shows Infected Undiagnosed (I_U), Infected Diagnosed (I_D), Susceptible Diagnosed (S_D), Exposed Diagnosed (E_D), and Removed_Diagnosed (R_D) cases; all diagnosed cases are isolated so this panel shows number of cases isolated by TTI over time. Middle-left panel shows numbers tested and traced over time. Middle-right panel shows number of contact tracers in each three-month block. Bottom-left panel shows testing costs per 6 month block. Bottom-right panel shows tracing costs per three-month block. Pink shaded band shows contacts per day (*c*); darker shading denotes more contacts per day. Blue shaded band shows testing rate; darker shading denotes higher testing rate. Green shaded band shows tracing rate; darker shading denotes higher tracing rate.

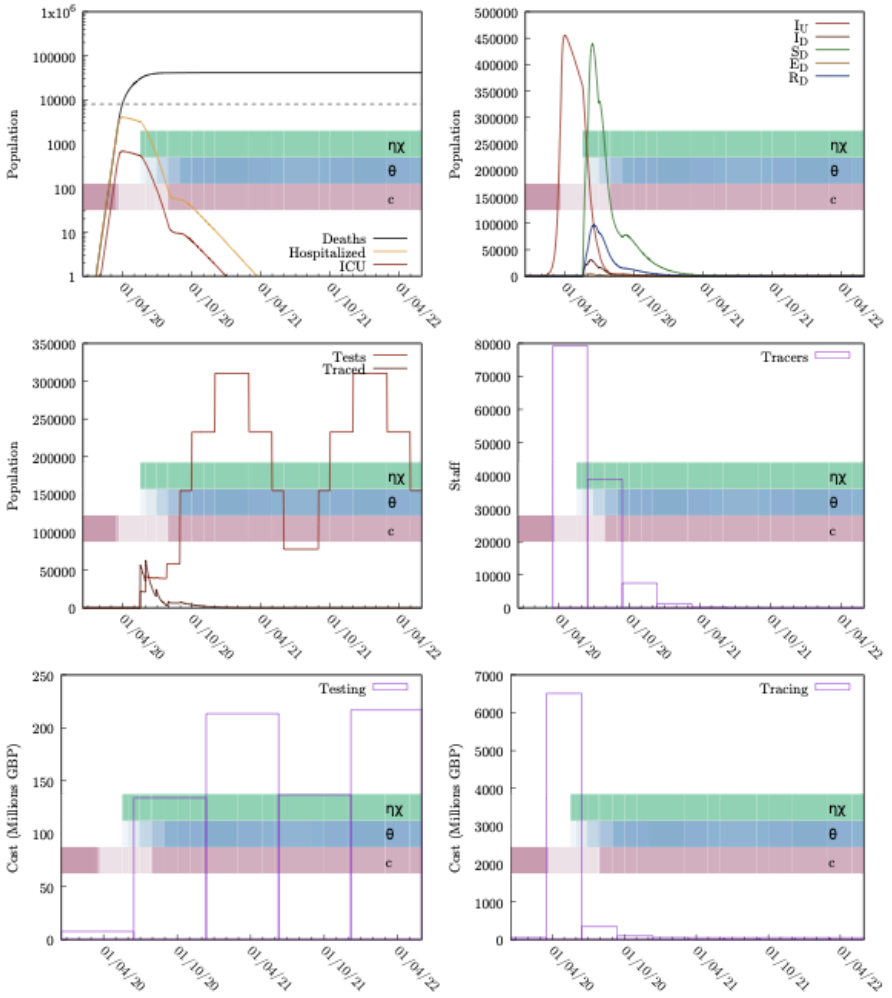
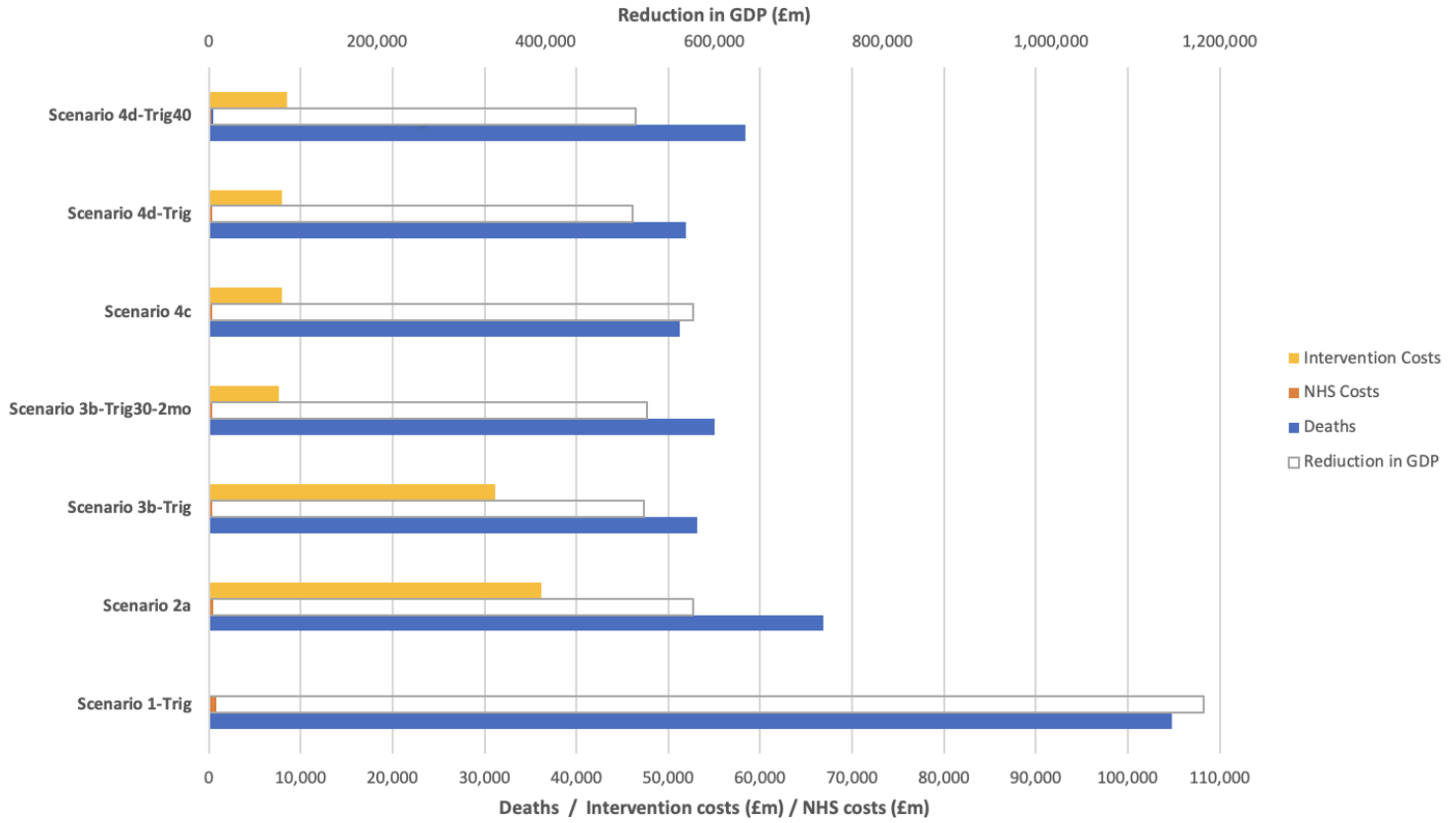


Figure 2 Health and Economic outcomes of selected Population-scale Testing, contact Tracing and Isolation (PTTI) strategies to control the COVID-19 epidemic in the UK – scenarios run to 31 May 2022. Scenario 4d-Trig-40 is targeted testing, face coverings, subsequently triggered lockdown, and 40% tracing success; scenario 4d-Trig is targeted testing, face coverings, subsequently triggered lockdown; Scenario 4c is targeted testing, face coverings, longer initial lockdown; scenario 3b-Trig30-2mo is untargeted testing, face coverings, longer initial lockdown, 30% tracing success, switch to targeted testing after 2 months; 3b-Trig is untargeted testing, face coverings, longer initial lockdown; scenario 2a is, untargeted testing, longer initial lockdown; scenario; 1-Trig is no TTI, subsequently triggered lockdown.



Discussion

Our results make a strong case for expanding testing and/or tracing immediately to control COVID-19 spread until a vaccine or highly effective drugs are available. We find that population-wide testing, contact tracing, and isolation (PTTI) strategies can help to suppress an outbreak rapidly and, once an outbreak is suppressed, prevent new outbreaks. This is possible without the need for subsequent lockdown, providing that testing and/or tracing programs are scaled up sufficiently during lockdown. We also show that population-wide use of face coverings in all public spaces can make all PTTI strategies more effective in suppressing the epidemic, with lower cumulative deaths and less time in lockdown, in addition to lower associated costs.

The best-case scenario involved targeted testing of symptomatic people with mandatory face coverings and a subsequent short lockdown to enable TTI scale-up to suppress the epidemic (scenario 4d-Trig). This requires approximately double the number of people tested per day in the summer compared to that currently achieved for community swab "Pillar 2" tests (as of 9 June 2020, number of people not shown so hard to estimate[33]). Of the modelled scenarios, this would result in the fewest COVID-19 deaths (~52,000), the lowest intervention costs (~£8bn), and £503bn reduction in GDP by 31 May 2022, including the costs already incurred due to lockdown and the pandemic: less than half the cost to the economy of subsequent lockdowns needed to control spread in a scenario without PTTI (scenario 1-Trig, ~£1,180bn reduction in GDP, ~105,000 deaths). The number of tests required would rise to approximately 300,000 tests per day in winter when there is a higher prevalence of cold and flu symptoms, which can be confused with COVID-19. Assuming 50% of COVID-19 infections are symptomatic, targeted testing of symptomatic people with 80% coverage should diagnose 40% of all COVID-19 infections. The epidemic can still be suppressed due to amplification of the effect of testing by tracing and isolation, i.e. assuming 64% are of their contacts are successfully traced (~80% have tracing attempted with 80% success) within the infectious period (most within the first two days and nearly all by seven days) and all are isolated – including those without any symptoms – for 14 days. This requires each new case to receive the full attention of a team of contact tracers as soon as it is identified.

Even though untargeted testing can also detect asymptomatic infections, it would need four million people tested each day to pick up the same proportion (40%) of infections, and is therefore much less efficient than targeted testing. Untargeted testing of everyone every week, if it were feasible, may work without tracing, at a higher cost (scenario 3b-Trig00). This cost could be reduced by switching to targeted testing after the epidemic is suppressed (scenario 3b-Trig30-2mo), though we note the epidemic could be suppressed with targeted testing itself providing tracing and isolation has at least a 32% success rate (*chi* 0.8, *eta* 0.4, scenario 4d-Trig40, Table 1, Figure 2).

We note that while we have looked at a variety of scenarios with variations in testing and tracing, we have not exhausted all possibilities. Testing and contact tracing individually have different scaling properties and can be mixed in different proportions. Testing alone scales linearly with the

population: a population twice the size requires twice the number of tests. It is therefore possible to suppress the virus with a strategy that tests everyone without tracing (scenario 3b-Trig00, Table 1, Figure S19). But to effectively suppress an outbreak using only testing, it has to be done sufficiently frequently and in a sufficiently large proportion of the population to be confident of identifying all infectious individuals. Because tracing follows the path of the outbreak itself through the population, the cost of tracing increases exponentially with the number of infections. When prevalence is high, it is theoretically more efficient and less costly to simply test the entire population. However the infrastructure in the UK could not deliver this in the necessary timeframe. When prevalence is low, a far smaller number of tests is needed, and rapid contact tracing becomes feasible and less burdensome. Thus, the best strategy, whether frequent testing or combining scaled testing and tracing, depends on the prevalence within the population. Our study gives insight into this and aims to inform the policy decision makers.

The combination of economic, policy, and epidemiological concerns is critical and our work is the first to shed light on all three. Firstly, our analysis, unlike others to date,[34,35–38 39] includes a comprehensive economic evaluation as well as impact evaluation. While modelling is crucial to understand how to prevent morbidity and mortality from the SARS-CoV-2 virus, there may be a trade-off between saving lives and protecting the economy as we move forward out of the lockdown.[40] Our study is the first to evaluate the costs of different exit strategies, giving feasible options that can both save lives and protect the economy.

Secondly, we modelled testing, tracing, and isolation strategies in a novel way. Previous approaches have either been too simple to accurately capture both the epidemiological and economic effects of TTI or too complex for rapid and flexible exploration of policy options. The simple approach which asserts that TTI modulates the rate of disease transmission[34] or isolates a proportion of exposed individuals[35–38] does not adequately capture the dynamics of contact tracing.[25] An alternative is detailed individual-based models (IBMs) tracking the transmission of individuals,[39] and existing detailed IBMs come to broadly similar conclusions[41]. There is an overarching agreement that scaling of TTI is required to suppress the virus and keep it suppressed as we exit lockdown. Both papers suggest that testing and isolation is not sufficient to suppress the epidemic, and Panovska-Griffiths and colleagues[41] suggest that TTI should focus on scaling targeted symptomatic infection, with sufficient tracing and isolation of symptomatic and diagnosed positive individuals. Kucharski and colleagues suggest that for a large outbreak, suppression requires a significant reduction in contact rate for tracing to work.

Finally, the policy insight that can be derived from our work is useful. Other recent analyses of policies do not model contact tracing as an option,[42–44] leading to conclusions about tradeoffs between a non-exhaustive set of options. Others do model contact tracing as a policy option, but use a simplistic representation of contact tracing as noted above,[45] which does not allow consideration of the policy choices faced by decision makers. On the other hand, epidemiological studies that model tracing in enough depth to properly represent the dynamics and policy options find that it would be effective, but do so without without considering the economic impacts,[36,37,46–48] making it difficult to assess the actual policy tradeoffs involved in more or less restrictive versions of the policy. It is important to note that PTTI could be abandoned when drugs or a vaccine

become available without sunk costs being too high. Sunk costs are a low proportion of the total resources required as most of the resources are recurring (e.g. test kits, test processing) or in blocks of three months (e.g. salaries for contact tracers who are given 3 month contracts) or six months (e.g. laboratories, lab worker contracts; Table S2).

Some limitations to highlight are as follows. Our model does not distinguish between symptomatic and asymptomatic (or presymptomatic) infectious individuals. Our conclusion is that, given that contacts of confirmed cases are not tested in our targeted TTI scenarios, they must all isolate – not only those with symptoms – in order to achieve a sufficiently high rate of isolation of infectious individuals. This is crucial and indeed with tracing and isolation of asymptomatic and symptomatic infectious people the majority of all infections are still covered and the majority of subsequent transmission stopped (see supplement for a more detailed explanation). This is assuming infectiousness is not skewed towards the beginning of the infectious period.

Our model does not account for the variance in exposure that may be connected to the range of social and economic risk factors outlined in Table S3. Given PHE's recent report outlining the variability of impact of covid-19 between ethnicities, socioeconomic status and occupation,[49] this is an important caveat to make. While future modelling studies could be conducted to take these issues into account, the need would be diminished by our suggested community-led approach to PTTI implementation. The most valuable insights into vulnerability to infection, variability in exposure to risk, and ability to adhere to PPTI will be gathered from the general public themselves, so it is critical that systems be in place to collect and engage with this data regularly, rather than relying on modelling data alone.

The exact numbers of deaths averted depend on assumptions about the proportion of the country that has already been infected (6.8% in early May 2020 according to seroprevalence data for the UK[3]), and relatedly, the infection fatality rate. These parameters remain uncertain though we use what we believe are the best currently available estimates.[4,6,50] We focus on mortality, though chronic illness and organ damage from COVID-19[51] may have long-term effects not only on the health and well-being of the people affected but on the economy. We have not included these outcomes, so our conclusions on the potential benefits of PTTI are likely to be conservative.

Our model also simplifies the representation of isolation, by implicitly representing failures to isolate as contact tracing failures. We also do not model costs to enforce isolation, though unlike other studies, we do not assume perfection.[48] As noted above, the contact tracing success rate could be far lower than modelled, but unless compliance is less than half, corresponding to a success rate of 40% rather than 80%, these strategies can still be effective, albeit less so. Policies to support effective isolation, such as community support and volunteers to run errands for those isolated, are therefore potentially important. Also note that the costs of enforcement are assumed to be covered by a combination of using existing policing systems and paying for additional measures with fines gathered from violators. This may be optimistic, but the need to enforce

compliance is true of any infection control system, and is expected to have minimal impact on the relative value of the approaches – which still are far more effective than allowing uncontained spread.

A general point should be made about this class of model, independent of calibration or fitting of any particular parameter values. This is a well-mixed model, meaning that each non-isolated individual has an equal chance of encountering any other non-isolated individual. The effect of this structural assumption is that such models will tend to overestimate the spread of the disease. Real populations have more structure which means that the pool of susceptible individuals in a local contact network can become exhausted and retard the propagation of the virus through the population as a whole. We do not, however, have data to ascertain the magnitude of this effect. Simultaneously, the chance of a contact being traced is assumed to be proportional to having had at at least one infectious contact. An alternative formulation could be that the chance is proportional to the *number of* such contacts, which of course would mean that tracing should happen faster. Both of these structural assumptions act to systematically overestimate the severity of the epidemic and underestimate the effectiveness of contact tracing. As such, they err on the side of safety. If we construct a PTTI regime aiming to achieve the recommendations that we give here, we have some margin for error in the not unlikely event that we fall short.

All mathematical and computational models are simplifications and the one underlying this analysis is no different. There are several relevant phenomena that are only captured indirectly and could usefully be explicitly included in a more sophisticated model. The relevant distinction between asymptomatic and symptomatic individuals for the purposes of outbreak control is equivalent in this model to a reduction in the proportion of the population that is tested, in the cases where targeted testing is considered. Similarly for imperfect isolation: this is captured with a lower testing and/or tracing rate as no distinction is made between not isolating someone and isolating them and having them not comply. There is an asymmetry here, however, in that the economic impact of imperfect isolation is not accounted for. A lower rate of isolation not only means a lower rate for infectious individuals but also lower for those susceptible or recovered individuals erroneously isolated. We suspect that this effect will be relatively small but more work is needed to check that. Finally, this same asymmetry is present for imperfect testing: false negative tests are equivalent to a lower rate of testing but false positives are not accounted for i.e. we conservatively assume, invoking the precautionary principle, that they are subject to tracing and isolation too in order to suppress the epidemic. There is a trade-off between having a model that is rich enough to provide useful insights into which strategies for outbreak suppression are likely to work and having one that is so detailed that it is difficult to understand the underlying interactions and dynamics. We have deliberately chosen a simple model to understand the interaction between, and relative merits of, testing and contact tracing, and the economic implications of these strategies both individually and in combination.

Other significant uncertainties are the effects of lockdown on the UK economy and the costs of testing. For the effects of lockdown on GDP we assume GDP reduction scales with lockdown (c contacts per day) so is directly related to the time spent under lockdown, which in turn is related

to the scenarios we consider, including the scenarios where subsequent lockdowns are triggered when new cases go above 40,000 cases per day. Therefore, the ordering of the scenarios with respect to reduction in GDP will remain the same even if true GDP costs of lockdown are different to our assumptions. The costs of testing are converging around our estimate given new methodologies that can be applied at scale. Importantly, our conclusions regarding the need for targeted PTTI to suppress the COVID-19 epidemic in the UK instead of lockdown would remain relatively similar even if the deaths and cases averted, or the economic gains, were considerably lower.

Our results are presented as a disaggregated impact inventory rather than a cost-benefit analysis given that the latter would require a measure of an appropriate rate of trade-off between reductions in deaths and reduced GDP, which are available but likely to be contested. Because we calculate economic costs directly in relation to GDP, we do not include costs to the informal economy (care, voluntary work). We also do not make any assumptions or detail the distribution of economic (GDP) costs by type of work or any other disaggregation. Nor do we include the costs of any informal care received by COVID-19 patients (we only include NHS costs).

A fully operational integrated PTTI system is urgently needed to control and suppress the COVID-19 epidemic in the UK until a vaccine or highly effective drugs are available. There are still many obstacles to overcome for this to become a reality[52]. By clearly outlining the health and economic benefits that such a system could lead to, we hope the scientific advice and investment case we are providing helps to galvanise sufficient action to realise PTTI.

We provide decision makers with results that can be used to balance estimated deaths and morbidity averted with estimated economic outcomes of different policy options for controlling the COVID-19 epidemic in the UK. Our results depend on extensive expansion and quality control of TTI infrastructure. The political and public acceptability of the alternative scenarios need to take account of crucial implications for employment, personal and national debt, education and population mental health and non-covid health .

Contributions

TC, JP, NA, KMG and PR conceptualised the study and initially developed it with DF, GY, RB, DM, CaB, EP, MO, MS, MG and RR, and early analysis was done by GC and TC. The mathematical model used here was developed by WW, SS and JPG with input from TC and DM. The economic model used here was developed by DM and TC with input from WW, SS, JPG, EP, MG and MS. TC, WW, JPG, DM, SS, GC, CaB, KMG, DF, EP, TH, NG, NC, MS, and MG contributed parameter values used in the model or interpretation. The scenarios used in the study were developed by TC, DM, WW, JPG and SS in discussion with all co-authors. WW ran the modelling analysis with input from TC, JPG, DM and SS. DM and WW ran the economic analysis with input from TC, JPG, EP, MG and MS. TC, WW, JPG, DM, and RR led the drafting of the

manuscript and CaB, KMG, JP, RAB, GY, KO, PJR, TH, GC contributed specific sections of the manuscript. All co-authors provided critical feedback to several iterations of the paper and have read and approved the final manuscript.

Declaration of interests
All authors declare no competing interests.

Funding
WW acknowledges support from the Chief Scientist Office (COV/EDI/20/12) *RR, JPG and EP are supported by the National Institute for Health Research ARC North Thames. NMcG is a recipient of an NIHR Global Health Research Professorship award (Ref: RP-2017-08-ST2-008). The views expressed in this independent research are those of the authors and not necessarily those of the National Institute for Health Research or the Department of Health and Social Care. KMG is supported by the UK Medical Research Council (MC_UU_12011/4), the National Institute for Health Research (NIHR Senior Investigator (NF-SI-0515-10042) and NIHR Southampton Biomedical Research Centre (IS-BRC-1215-20004)), British Heart Foundation (RG/15/17/3174) and the US National Institute On Aging of the National Institutes of Health (Award No. U24AG047867). GY acknowledges her research partially supported from the Newton Fund through a UK-China ARM Partnership Hub award (No:MR/S013717/1).*

Data sharing
All data used in this paper is publicly available and referenced and our model is also publicly and freely available.

Acknowledgements
The following people have provided helpful comments or suggestions, or have otherwise enabled this work: Martin J Buxton, Majid Ezzati, Amy Gimma, Gabriel Goh, Grace Grove, Agnese Iuliano, Christopher Jarvis, Paula Lorgelly, Ofir Reich, Justin Shovelin, Mark E Thomas.

Supplementary material

Mathematical model

Standard compartmental models cannot represent exogenous effects such as tracing of contacts of infectious people except by arbitrarily adjusting disease transmission or progression. Agent-based, or branching process models are generally used for this purpose. Our extension of the SEIR model allows contact tracing to be incorporated in a way analogous to agent-based models, but in a deterministic, population-based way. The advantage is speed. The mean trajectory of the system can be computed in seconds, even for the whole population of the UK. A comparably sized agent-based model would take hours or days. This speed means that it is possible to explore the space of different scenarios and interventions very rapidly.

In brief, we extend each of the standard S, E, I, and R compartments with unconfined and isolated variants. Infectious individuals become isolated due to testing. We assume that this isolation is perfect and that they no longer cause infections. We track contacts, whether or not causing infection, using an additional four pseudo-compartments, which do not represent subpopulations but the propensity of each subpopulation to be traced. This allows cohorts of tested, contact-traced, and isolated to be overlayed on the classic cohorts of S, E, I, and R, and allows a person to simultaneously belong to more than one population group. Specifically, within the model, each compartment includes subgroups of people diagnosed and undiagnosed with the virus, attributable to reported and unreported diagnosis, with diagnosed people identified either through testing or through tracing. Individuals diagnosed positive to infection are then isolated. A schematic of the model is shown in Figure S1 below, reproduced from the preprint. A full description and equations of the model are in the preprint.[25]

The model is formulated as a system of ordinary differential equations. This means that all rates imply *expected* values for the timing of events. On average, an individual is isolated for 14 days. This is equivalent to isolating half an individual for four weeks, or two people for a week. Expecting to wait 2 days for a contact to be traced and succeeding in tracing 80% of is equivalent to expecting to wait 2.5 days to be traced with certainty of all contacts being traced or 30 hours with 50% success. All of these rates and time intervals should be understood as expected values for large populations and do not make sense for small populations or individuals. The *meaning* of these parameters is a matter of interpretation not uniquely determined by the model itself.

Tracing in the model is defined via the parameters chi and eta where 1/chi is the average time it takes for a contact to be traced and eta accounts for the efficacy of contact tracing (the proportion who are successfully traced and isolated). So if the average time for a contact to be traced is 2 days then chi=0.5, and if the efficacy is eta=0.8 then the overall effective tracing level will be 40%, while if average time for a contact to be traced is 1.25 days then chi=0.8, and if the efficacy is eta=0.8 then the overall effective tracing level will be 64%

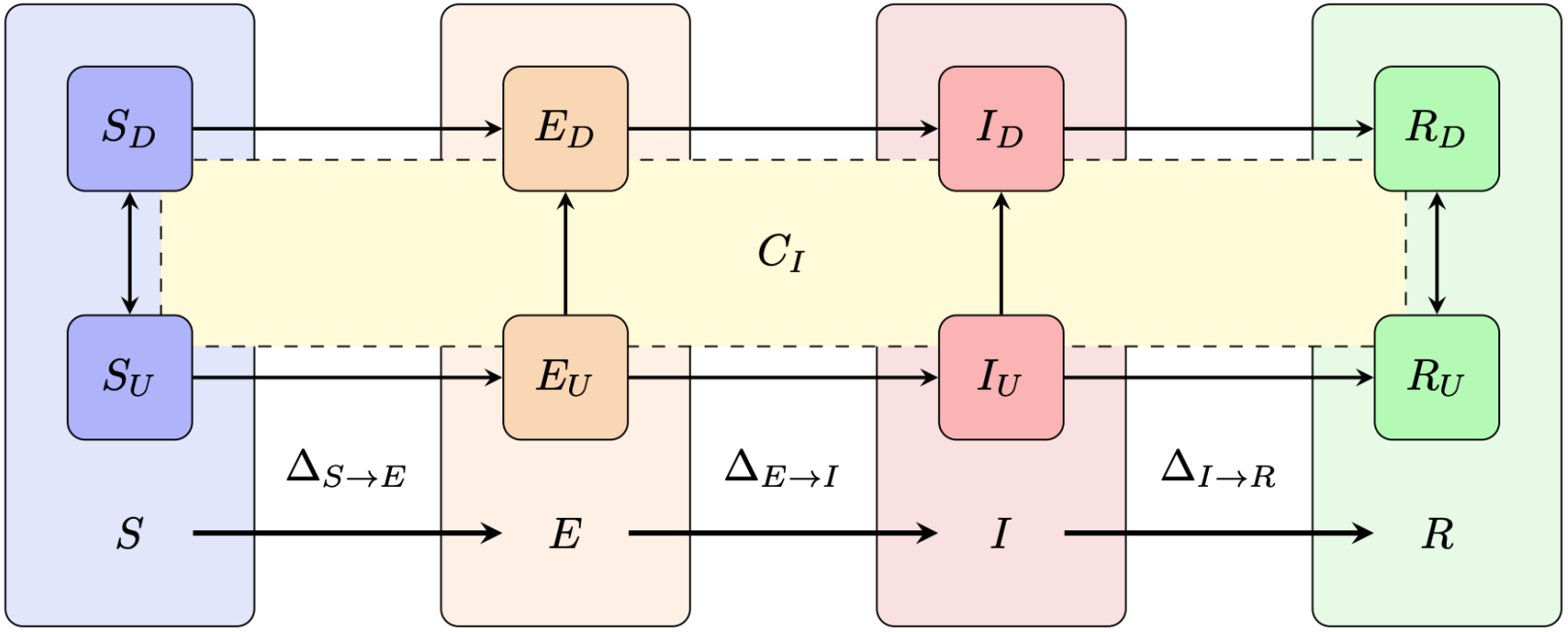


Figure S1 Schematic of an SEIR model with diagnosis described by testing and contact-tracing. SEIR is a compartmentalised model describing susceptible (S), exposed (E – infected but not infectious), infectious (I) and removed (R) population cohorts. Individuals move between these compartments in sequence as they become exposed, infected and infectious during disease progression until recovery. The novelty here is that each compartment comprises diagnosed (D) and undiagnosed (U) individuals with diagnosis leading to isolation. We assume that diagnosis

happens through testing or putatively through tracing. Individuals transition between compartments X and Y at rates $\Delta X \rightarrow Y$ which we derive in the text.

Interventions and triggers

We further extend the model framework described above with interventions and triggers. Interventions change model parameters at specific times. Triggers change model parameters when a condition is met, for example the number of infectious individuals rising above or falling below a certain threshold. Both of these mechanisms change key model parameters such as the contact rate (to represent distancing measures), testing and tracing rates (as capacity is added), and the probability of infection per contact (for measures such as wearing face coverings). The above model is simply simulated piece-wise, holding these parameters fixed, between interventions or trigger points.

Model parameterisation

The SEIR-TTI model was developed previously[25] and is shown schematically in Figure S1. The model was parameterised using existing literature. Parameters used for the purposes of this analysis are shown in Table S1. Specifically, we use estimates of exposure time of 5.1 days and the infectiousness period of COVID-19 of 14 days. We use an estimate of 11 social contacts per day (c) at baseline from the recent BBC Pandemic social mixing study for the UK,[53] which aligns with earlier UK data on social contacts.[54] We then make a modelling assumption that social contacts were reduced by 30% from 16 March 2020 under the voluntary physical distancing measures and the hygiene campaign in the week before the lockdown. Then we use an estimate of a 70% reduction in c from lockdown on 23rd March 2020,[55] which we assume applies for the duration of the lockdown. For the relaxation of lockdown we use an estimate of c increasing to 40% of baseline from 13th May 2020[56], then assume c increases to 60% of baseline from 1st June when schools partially opened, and to 80% of baseline from 4th July when entertainment venues may open in line with the UK government phased opening approach.

We assumed an infection fatality rate (IFR) of 1%, taking into account a recent estimate of 0.66% in China,[50] the UK age at death being slightly higher than in China, and older people having a higher IFR.[50] Recent seroprevalence surveys also suggest IFR may be around 1%: an estimated 6.8% of the UK population (95% CI: 5.2% to 8.6%) – around 4.5 million individuals – had antibodies to SARS-Cov-2 as of May 24th 2020,[3]

while deaths were estimated at 37,000,[57] implying an IFR of 0.8%, and may have been as high as 60,000,[58–60] which would indicate an IFR of 1.3%.

Table S1 Model parameters

Parameter	Description	Default Value*	Reference
N	Population size (UK population mid-year 2020)	67,886,011	[61]
c	Average contacts per day	11	[53]
β (beta)	Transmission rate per contact	0.0425	Estimated from fit to mortality data[57]
α^{-1} (alpha)	Incubation period (time from exposed to infectious)	5 days†	[62–65]
γ^{1} (gamma)	Recovery period (time from infection to recovery or hospitalisation)	7 days†	[66,67]
κ^{-1} (kappa)	Isolation period (symptom free days)	14 days	[68]
θ (theta)	Testing rate of infectious individuals	0	-
χ (chi)	Contact tracing rate	0	-
η (eta)	Efficiency or success rate of contact tracing	0	-

* values used in modelled scenarios shown in Panel 1
† values from the literature come with wide confidence intervals

Model calibration

Calibration of the model projections to available data is described in detail and visually shown in the documentation for our software.[2] Briefly, we match the number of model projected deaths to the reported UK deaths associated with COVID-19, using an infection fatality rate (IFR) of 0.8% and a lag from infection to death of 18 days, setting the number of contacts per day in relation to pre- and post-lockdown periods and varying the transmission probability (β). In addition, to match the epidemic trend in terms of reported numbers of cases for the UK, we also varied the seeding date of the UK epidemic, estimating the onset of the UK epidemic to be 18 December 2019 and a β of 0.0425 (which translates to a basic reproduction number [R_0] of 3.3 when c is 11 contacts per day when there are no interventions). We note that while we have taken 18th December 2019 as the date for the onset of the epidemic in the UK, as a modelling assumption, it is possible to also fit the initial epidemic with other dates. In fact, the fit to the data is not strongly sensitive to the onset date largely because the greatest weight of the data is for the lockdown period where R is near to 1 and the data from before that time is of poor quality.

Asymptomatic individuals

The model does not distinguish between individuals of differing symptomaticity. In reality some proportion of infected individuals will display very mild or even no symptoms. So long as this proportion of is less than half, the majority of cases can be identified by having symptoms and testing. If the testing rate θ is thought of as the rate of testing all infectious individuals, then a circumstance where half are symptomatic corresponds to a testing rate of $\theta/2$. Tracing, however, operates on the subsequent generation, the contacts of those who are tested. Here again we have the same choice. If we suppose that all contacts are isolated, then this corresponds to a success rate of isolating infectious contacts of η**.** If only those that are symptomatic are isolated, then properly the rate should be $\eta/2$. Which of these choices is used is a matter of convention. Here we adopt the convention that all contacts are isolated regardless of symptomaticity.

[2] https://github.com/ptti/ptti/blob/ptti-preprint/README-Assumptions.md#fitting-the-data

Economic Model

NHS costs

NHS costs are based on the proportion of cases hospitalised and the proportion requiring intensive care unit (ICU) care. These are calculated as a proportion of total infections, using an estimate of deaths in and out of hospitals, and hospitalisation rates. This is a two step process: we first transfer from cases to deaths via the IFR, and then we assume that the reported deaths are only a proportion of all deaths. Specifically, we make a modelling assumption that the reported COVID deaths due to hospitalisation are 60% of all deaths, with the remaining 40% occurring outside of hospitals (mostly in care homes). This assumption is based on there having been 29,227 reported hospital deaths due to COVID-19 in England and Wales from 28 December 2019 to 29 May 2020, out of a total of 45, 748 COVID-19 deaths in the same period[69] – we assume the same split for the whole UK for the whole epidemic.

ICU and non-ICU hospital cases are then estimated using the number of hospital deaths, based on the data on the proportion of deaths in ICU and non-ICU patients for COVID-19. We use available literature to quantify that 53.6% of ICU cases[70] and 36.3% of non-ICU hospitalised cases die due to COVID-19.[70] We combine this with the estimated percentage of overall hospital cases in the ICU, and this percentage is also then used to find total ICU cases.

NHS unit costs are estimated from the literature and are set at £1,675 per day per ICU case[71,72], factoring a mean of 3 organs supported[73]; and £346 per day for non-ICU cases.[74] ICU cases are assumed to require eight days based on the median length of ICU stay in England, Wales, and Northern Ireland, and non-ICU cases seven days.[70] Deaths are taken as costing £500.

Reduction in GDP

We calculate reduction in GDP due to the pandemic and lockdown measures by relating GDP to the model parameter *c* (contacts per day) as a proxy for economic activity, for every day of the model scenario trajectory. GDP of £186 billion per month is taken as the pre-pandemic level,[75] when $c = 11$, whereas during lockdown GDP is 25% lower, when $c = 3$. For intermediate values of lockdown or distancing, GDP loss is scaled accordingly. The pandemic itself results in GDP loss, as $c = 80\%$ of baseline even when lockdown is fully released, i.e. things are not back to $c = 11$ (100%) normal economic activity.

Intervention costs

Intervention costs are calculated by dividing the budget items shown in Table S2 by start-up costs and on-going costs: for tracing, and for testing. Costs to notify, enforce, and otherwise manage isolation are assumed to be covered by fines levied for breaches of isolation. Overall start-up costs for contact tracing are £10m for the app that supplements human contact tracing efforts, as well as a recruitment campaign to hire the number of needed contact tracers, supervisors, and managers. Start-up costs include recruitment and training costs for personnel, and app maintenance costs, for which we have made several assumptions detailed in the appendices, though these are small enough not to significantly alter overall costs. On-going costs are scaled according to the numbers required by the intervention by estimating the cost per contact traced and the cost per test, as follows.

Contact tracing costs

Using our assumptions around number of contacts before lockdown (c0=11), during lockdown (c=0.3*c0), and after the lockdown is lifted (c=0.8*c0), we determine that over a period of 7 days a total of 77 contacts need to be traced before lockdown, while during lockdown only 23 contacts will need to be traced.

As a policy design assumption for the model, we stipulate that contact tracers and supervisors are hired for a minimum of three months (90 days) for the system to function professionally, while team leads are hired for the entire term of contact tracing. Contact tracing costs are therefore blocked into 3 month periods based on the anticipated maximum number of tracers needed in the subsequent three-month period. Recruitment and training costs for any additional tracers needed in the subsequent three-month period are added to the cost for that three-month period.

The recurring tracing costs can be used to determine a (marginal) cost per hour of tracing, which can then be used to determine the cost per trace given our estimate of 1.26 hours work per contact traced (Table S4). We estimate the cost per contact traced is approximately £18 (calculations as per 'Tracing costs per case traced' sheet here).

Testing costs

We estimate that each test costs £4.79 including start-up and recurring costs. The vast majority of these costs are the £4.50 for each actual test (£3.50 for the test kit, £0.50 for mailing out the test kit, and £0.50 for the courier from the tested person's address to the local lab). Start-up costs for testing are the cost of the RT-LAMP machines (£27,000 each). Each machine can run 96 tests every 30 minutes[76] so if we assume they will be

running for 18 hours per day (two nine-hour shifts) they will process 3,456 tests per day. We assume 10 machines per lab on average, each with £500 per day overheads, 40 lab workers (four per machine: two for each shift), and two supervisors (one for each shift).

Testing personnel costs are blocked into six-month periods based on the anticipated numbers of tests per day over the subsequent six-month period. In a six-month period where only 100,000 tests are being done each day, costs per test would still be approximately £4.79, as the number of labs, maintenance costs, and lab workers would be scaled down accordingly, and the RT-LAMP machines would be amortized over the full period of use.

Table S2: PTTI Resources Required
Shown are unit/daily costs. Total costs are variable dependent on policy scenario and case numbers.

1. Contact tracing

Staff	Function	Number	Uncertainty*	Rationale for number	Salary per day	Notes
Public Health Community Officer	Trace contacts via apps and in person - follow-up to check isolation and re-testing	81463	10000	1 per 1000 population (like community health workers in many countries) + 20% for sickness cover and absence	£80	These workers can be people who have lost their employment as a result of the lockdown, they will need minimum qualifications though no prior experience of public health work as can be trained
Public Health Covid supervisor	Supervisor / manager for PHCOs - ~1 per 50, or ~4 per each of the 343 local authority areas	1629	400	these team leads will work full time answering queries from PCHO and helping resolve problems + 20% for sickness cover and absence	£160	These supervisors could be recent graduates of public health or related Masters courses, or local authority Environmental Health Officers.
Local authority team lead	One for each of the 343 Local authorities	412		1 for overall control of contact tracing effort for each local authority area + 20% for sickness cover and absence	£300	These team leads should be public health specialists with at least 5 years experience
Online training for all staff		1	0	Three training courses (including refreshers) one for each staff cadre. Assume repeated every 3 months		generously funded at £20,000 per online training course developed (can do on phones which will be used for contact tracing too) + £500 per month for running servers for online training
					Unit cost	

Recruitment costs	Recruitment costs for all contact tracing staff, including for replacements and cover (per 3 month period - conservative assumption is repeating this every 3 months even though the same tracers may be in post)	83504	8,350	£200 per recruitment for advertisements, phone interviews, salary of recruiters	£200	
Equipment	**Function**	**Number**	**Uncertainty***	**Rationale for number**	**Cost per day**	**Notes**
Phone pay as you go credit	for calls and data for all staff including for online training	83,504	10,400	all staff above	£5	
					Unit cost	
Smart phones	only for ~10% of staff who don't have one	8,350	1,000	most people have smartphones in the UK	£200	
START-UP COSTS:						
Mobile phone app development	for rapid contact tracing given rapid spread	1		one app needs to be developed (or chosen from many already made?)	£10,000,000	ballpark estimate of developing, maintenance and running the app over a year
3 MONTH PERIOD COST:						
Mobile phone app maintenance and running costs	for rapid contact tracing given rapid spread			£1m per month estimate means £3m per 3 month period	£3,000,000	
Travel					**Cost per day**	
For supervisors and managers	to check work of PCHOs in person if needed	2,041	1,000	number of supervisors and managers	£10	Travel will be in local areas so costs per day for driving or public transport should not be high

For PCHO in rural areas	to get around to their whole catchment population of 1000 people	13,849	5,000	17% of UK population is rural so have this travel allowance for 17% of PCHO	£10	Travel will be in local areas so costs per day for driving or public transport should not be high
3 MONTH PERIOD COST: Communications	To advertise the contact tracing scheme and keep people informed of it	1	4,562,500	Estimated budget of £100,000 per day for advertising and communications. Advertising campaigns assumed to last for a minimum of 3 months	£9,125,000	This will be additional to national COVID-19 advertising budgets given current on-going COVID-19 advertising campaigns funded by the government

2. Testing - SARS-Cov-2 viral RNA RT LAMP tests, home saliva samples

Staff	**Function**	**Number**	**Uncertainty***	**Rationale for number**	**Salary per day**	**Notes**
Lab technicians	running SARS-Cov-2 viral RNA RT LAMP tests	11,574	1,157	18 hrs per day, two 9 hrs shifts: 1 technician running one machine, and 1 filling the wells per machine. So 4 shifts per day. Automated reporting into LMIS system - electronic connection into health records automatically.	£200	
Lab supervisors	supervising lab	579	58	two one for each lab (one for each 9hr shift) - average 10 RT LAMP PCR machines per lab	£300	
Lab staff training	training on running RT LAMP tests	12,153	1,215	Initial 2 day training, 1 day refresher every 3 months	£200 **unit cost**	5 days training per year
Recruitment costs	Recruitment costs for all lab staff, including for replacements and cover	12153	1,215	£200 per recruitment for advertisements, phone interviews, salary of recruiters	£200	

Overheads						
Lab overheads	Overhead (space) costs for ordinary laboratory with category 2 hood (no biosecurity)	579	58	Estimated cost of £500 per day per lab for 289 labs with 10 RT LAMP PCR machines in each	£500	
Machines					**RT LAMP machine cost per day**	
START-UP COSTS: RT LAMP PCR Machines	SARS-Cov-2 viral RNA RT LAMP testing. Also automatically uploads data to online health records	2,894	289	Enough RT LAMP machines for 10 million tests a day if running 6 days a week 18 hrs a day, one 96 well plate per 30 minutes (20 min start to finish and 10 min turn around per run). One RT LAMP machine costs £27,000. Having this as an annual cost (per day calculated in caell F33) assumes all machines will be replaced after 12 months on average	£214,041	Total cost per year based on daily cost. If extending time beyond one year can use this as it is based on daily cost i.e. assumes RT LAMP machine lasts for 1 year or average and will then be replaced
RT LAMP PCR Machine maintenance	maintain working order of the 2894 RT LAMP PCR machines used	2,894	289	assume maintenance costs averaging £10 per day	£28,935	
Equipment					**Unit cost**	
Test kits, including reagents	viral RNA RT LAMP tests, home saliva samples. RT LAMP is at room temperature and doesn't require RNA extraction, so less reagents needed	3,120,000,000	312,000,000	10 million tests per day: https://www.bmj.com/content/368/bmj.m1163	£3.50	Reagents and materials per test - commercially sensitive source - used for pilot study costing
Home collection of saliva samples	To collect saliva samples by courier to the lab for testing	3,120,000,000	312,000,000	10 million tests per day: https://www.bmj.com/content/368/bmj.m1163	£0.50	Home collection by couriers - used for costing for planned pilot study
Tests Per Day		10,000,000				

3. Isolation encouragement

These costs are all covered under 1. Contact tracing.	**Number**		**Unit cost**	**Notes**

There may be additional policing costs estimated at £500 for every infringement requiring police action - estimated at 2000 such infringements per day nationally based on France and Italy	624,000	£500	These costs should all be (more than) covered by the fines levied and received for infringements, so are not included in total costs below

*Very rough guessed +/-, for now.

Additional health and social costs of lockdown

Table S3 shows potential health and social costs of lockdown that are not included in our economic model.

Table S3 Potential Health and Social Impacts of COVID-19 lockdown and impact on NHS of COVID-19 demand[77]

Sector			Processes affected	Potential adverse health outcome
NHS	Programmes	Screening across the lifecourse, e.g. neonatal, cancer	Delivery, uptake and action	Avoidable morbidity and mortality
		Immunisation	Reduced uptake	reduced herd immunity increase in vaccine preventable infection
	Child and adolescent health		Health visitor checks and support for parents Adolescent mental health Safeguarding	Avoidable morbidity Increased violence against children/child abuse while in lockdown (particularly linked with alcohol, drug use)
	Maternal health	Antenatal care in pregnancy and post-natal follow up	Birth experience Anxiety - giving birth alone/impact of self-isolation – reduced peer and family support for new mothers Missed risk factors and antenatal diagnoses	Adverse birth outcomes Postnatal depression
	Severe trauma		Still managed but Intensive Care Unit (ICU) availability may be stretched Secondary infection in hosp COVID-19 acquired	Avoidable morbidity and mortality
	Cancer	Potential new cancer Existing cases	Delay diagnosis and treatment Radiotherapy and chemotherapy	Avoidable morbidity and mortality
	Acute cardiovascular disease (CVD)		Still diagnosed and treated Secondary acquired in hospital Covid19 ICU availability	Avoidable morbidity and mortality, including from delayed presentation to hospital for CVD/acute MI

Other acute care (respiratory, fall, outpatients etc)		Diagnosis and treatment	Avoidable morbidity and mortality
Chronic disease management		Less monitoring (e.g. hypertension, diabetes, asthma, epilepsy) Poorer control Access to medication Difficulty following healthy lifestyle advice	Avoidable morbidity and mortality
Elective surgery		Delayed, Quality of Life (QoL) may worsen, less operable if condition worsens. Backlog	Avoidable morbidity Poorer Quality of life
Services for vulnerable groups	Homeless	Temporary housing provision, but often without access to food or basic necessities Lack of access to health services Disrupted support services during lockdown Removal of temporary housing at the end of COVID-19	Poorer health outcomes
	Dementia	Isolation, less carer support Harms e.g. falls	
	Patients with disability	Access to services for complex medical needs Isolation Anxiety – may not be a 'priority' group for ICU	
	Severe mental illness (inpatient services)	Deterioration, relapse? Loss of access to inpatient services (secondment of staff to Covid-related support) Reduced community mental health teams during lockdowns	Suicide Hospital Admission
	Prisoners	Mental health, addiction, COVID-19 risk Isolation (due to loss of visitation rights) Difficulty in isolation Risk of riots (like in Italian prisons)	
	Older people	Likely to live alone and have less access to online communication	Health impacts of isolation and loneliness
	Refugees and migrants	Exclusion of migrant populations from health services: NHS Charging Regulations deter migrants from accessing health services (particularly those undocumented) Culturally or linguistically inappropriate care	Poorer health outcomes Higher COVID-19 mortality for BAME groups[78]

			Increased discrimination/xenophobia during COVID-19 Difficulty in isolating or applying preventative interventions for those living in overcrowded conditions, intergenerational households, or those held in detention centres Low-wage migrant workers on precarious contracts	Higher morbidity and mortality from COVID-19 due to delay in accessing health service/lack of access to health service/ inability to apply preventative interventions Higher exposure to COVID-19 if continuing to work as key worker during lockdown; additional adverse effects of loss of income if precarious employment
		Health and care staff	Post Traumatic Stress Disorder (PTSD) Generalised Burnout	
	Diagnostic services X-Ray, Escopy		Delayed diagnosis and treatment	Poorer long term outcomes (avoidable morbidity and mortality) - Costly for individuals and the NHS
	Rehab Physio/Occupational Therapy		Poorer long term outcomes	Increase in disability or duration of recovery, poorer QoL – additional individual and societal costs
	Addiction services	Smoking cessation Alcohol Drugs	Some success with quitting Less support for dependent patients	Avoidable morbidity and mortality
	Sexual health services		Less access	Avoidable morbidity
	End of life care		Impact on hospices and care for those dying at home - reduced staff and funding Adverse grief reactions for bereaved rels of COVID-19 pts - evidence suggests that there will be increased rates of PTSD and depression for those affected by COVID-19 related loss, as it is essentially a form of traumatic loss – unexpected and without closure.	
	Mental health services (common mental disorders)	Increased rates of suicide and self harm[79] Increased rates of depression[79] Increased rates of condition related anxiety (COVID patients)[79]	Difficulties accessing primary care for early diagnosis and treatment	Avoidable morbidity and mortality

Social isolation and distancing measures	Household isolation		Less physical activity Mental health (stress, insomnia, anxiety, depression) Domestic abuse Family breakdown Elder abuse Safeguarding Loneliness Infection transmission from crowding Increased substance misuse Poorer diet (BMI impact, type 2 diabetes risk) Reduced access to medications Increased experiences of racialised policing (BME groups) Loss of access to public spaces (closure of parks likely to impact communities who live in crowded housing) Lack of access to free school meals for children who need them, and increased use of food banks	Depression Suicide Physical trauma Adverse impact on physical WB Increased falls in the elderly isolated at home Poor reporting of moderate health risks to health professionals (i.e. early signs of cancer, heart disease, etc)
	Access to food	Esp if vulnerable and isolating	Hunger, poor nutrition (both obesity and under-nutrition / vitamin deficiencies)	Adverse impact on mental and physical wellbeing and on child development
Transport	Less travel		Fewer accidents Less air pollution, including greenhouse gases	Less trauma from RTAs and therefore reduced admission to hospital Less cardiovascular, respiratory illness Less morbidity and mortality Increased health risks to those who continue support of essential transport services and their households
Employment /income loss	Household income loss on top of existing poverty especially those made unemployed, reduced hours outside Chancellor's support initiatives	Vulnerable groups for pre-existing poverty, low pay sectors (accommodation, catering, retail, care) Single mothers with children, People with disability, ethnic minorities	Food insecurity–hunger, nutrition Heating costs, cold related illness Mental health including alcohol and drug misuse (see above) Homelessness/loss of home Gambling Increased uptake of universal credit system due to lack of protection for economic shocks in poor households	Increased vulnerabilities Avoidable mortality and morbidity among already high risk groups
School closure	Education		Loss of free school meals if not attending school Loss of regular physical activity	

	Impact on social development and education (widening inequalities) Safeguarding
Higher education closure	
Longer term wider inequality post COVID-19	

Realising the Resources for PTTI

1. Contact tracing

There is emerging evidence that mobile phone contact tracing apps can facilitate effective COVID-19 epidemic control at scale and at speed.[80] Nevertheless, personal follow-up on foot will also be required to ensure all contacts, including the most vulnerable, are reached.[81] The additional costs of such a system are relatively small in the context of the problem we are seeking to address.

For feasibility reasons, we assume that control of COVID-19 would be managed through local authorities by Consultants in Health Protection/Communicable Disease Control and Directors of Public Health. This was the approach used, with success, until the re-organisation in 2002 and it ensured effective control of communicable disease via local knowledge of and relationships with the community, the local politicians and leaders, the laboratory, the hospital and its consultants, and the general practitioners.[82,83] Legal powers to take such responsibility are available through Schedule 21 (powers relating to potentially infectious persons) of the Coronavirus Act 2020. Regional Health Protection Teams from Public Health England could take on management responsibilities for local authorities in England (public health functions are already devolved in Scotland, Wales, and Northern Ireland) and co-ordinate regionally and centrally through its established infrastructure. This includes regional epidemiologists who have a key role in understanding the epidemic at a regional level, identifying differences between local authorities, and sharing expertise.
Movement of people between local authority areas could be accounted for by data sharing between contact tracing teams. China, while being different in many ways, demonstrates the ability for this hierarchical approach to succeed in identifying contacts.[84]

Case finding and contact tracing
Contact tracing remains a key control measure for maintaining suppression of case counts.[85] Table S4 shows the staff needed to handle new cases and control spread through contact tracing and quarantine.[86] Table S5 shows the hours and full-time equivalent staff required on the last days of May and June.

The NHS Test and Tracing Service was launched on 29th May. While information on the structure, duties, and means of collaborating with the contact tracing teams in local authorities has not been published, it is reasonable to assume that this centrally managed service will provide some of the hours required to run the case finding and contact tracing function shown in Table S5. It seems that the service is limited to phone and internet communication with individuals. Because the levels of ascertainment of cases and contacts and the compliance to quarantine of such an approach is unknown, it will be prudent for local authorities to assume that at least half the manpower shown in Table S5 will be required by them.

Table S4 – Hours required to identify contacts of each new case based on European Centre for Disease Prevention and Control guidelines

Contact tracing resources required for each new case	Public Health Community Officer (PCHO) hours
Interview new case and create list of contacts (45 min - 1hr)	0.85
Interview 14 high-risk* contacts (20 min each)	4.6
Interview 16 low-risk† contacts (10 min each)	2.7
Monitor 14 high-risk contacts daily for 10 days (10 min per call)	23.3
Monitor 16 low-risk contacts for 10 days (1 min per call)	2.7
Arrange to test symptomatic contacts (a) (10 minutes)	0.6
Car service taking 1 hour to test 50% of symptomatic contacts	3.1
Total hours	**37.8**
(a) Assume 3.7 symptomatic contacts per new case (URTI prevalence of 42/1000[87] and R_0 of 2.5[88])	

***High-risk** exposure contacts are people having had face-to-face contact with a COVID-19 case within two metres for more than 15 minutes; having had physical contact with a COVID-19 case; having had unprotected direct contact with infectious secretions of a COVID-19 case (e.g. being coughed on); having been in a closed environment (e.g. household, classroom, meeting room, hospital waiting room, etc.) with a COVID-19 case for more than 15 minutes; or a healthcare worker or other person providing care to a COVID-19 case, or laboratory workers handling specimens from a COVID-19 case, without recommended PPE or with a possible breach of PPE.[89]
†**Low-risk** exposure contacts are people having had face-to-face contact with a COVID-19 case within two metres for less than 15 minutes; having been in a closed environment with a COVID-19 case for less than 15 minutes; having travelled together with a COVID-19 case in any mode of transport; or a healthcare worker or other person providing care to a COVID-19 case, or laboratory workers handling specimens from a COVID-19 case, wearing the recommended PPE.[89]

Table S5 – Staff required to contact trace in each nation and English region on 31st May and 30th June

	Nation				English region									Country
	Scotland	Northern Ireland	Wales	England	North East	North West	Yorkshire and The Humber	East Midlands	West Midlands	East	London	South East	South West	UK
COVID-19 associated deaths registered by 11 May* of deaths in week ending 1st May	525	124	242	4,744	318	735	541	378	515	480	474	701	357	5,635
30th April new cases estimated from Scenario 1	5,151	1,217	2,375	46,548	3,120	7,212	5,308	3,709	5,053	4,710	4,651	6,878	3,503	55,291
31st May new cases estimated from Scenario 1	1,046	247	482	9,453	634	1,465	1,078	753	1,026	956	945	1,397	711	11,229
30th June new cases estimated from Scenario 1	168	40	78	1,521	102	236	173	121	165	154	152	225	114	1,806
Contact tracing resources required for each new case (hours, 37.8 hours per case) 30th April	194,720	45,991	89,757	1,759,526	117,945	272,608	200,654	140,198	191,011	178,030	175,804	259,997	132,410	2,089,994
31st May	39,545	9,340	18,228	357,336	23,953	55,363	40,750	28,472	38,792	36,155	35,703	52,802	26,891	424,449
30th June	6,361	1,502	2,932	57,481	3,853	8,906	6,555	4,580	6,240	5,816	5,743	8,494	4,326	68,277
Number of contact tracers required for each new case to be traced in one day (7.5 hours work per contact tracer per day) on 31st May	5,273	1,245	2,430	47,645	3,194	7,382	5,433	3,796	5,172	4,821	4,760	7,040	3,585	56,593
Number of contact tracers required for each new case to be traced in one day (7.5 hours work per contact tracer per day) on 30th June	848	200	391	7,664	514	1,187	874	611	832	775	766	1,133	577	9,104
Contact tracers per case														

5.1 5.1 5.1 5.1 5.1 5.1 5.1 5.1 5.1 5.1 5.1
5.1 5.1 5.1

*Note: The latest ONS report on COVID-19 associated deaths relate to those registered by 11 May of deaths that occurred in the week ending 1 May. These can be used as a proxy for the distribution of new cases within the country, the totals of which are derived from Scenario 1.

Local public health capacity

Each new case will require 38 hours of community health staff and volunteer time to trace an average of 30 contacts and test 3.7 symptomatic contacts, two thirds of whom will have COVID-19[86] (these numbers in Table S5 reflect a situation when physical distancing measures are in place). The requirement for staff will vary with time as relaxation of physical distancing increases contact numbers or as subsequent physical distancing reduces contact numbers, and should decline if phone applications as used in South Korea[90] are used by sufficient numbers of individuals here and their accuracy increases. On average there will need to be 5.1 full time trained contact tracers (Public Health Community Officers, PHCO; Table S2) to cope with each additional concurrent case. The numbers of contact tracers will need to be adjusted accordingly to accommodate part-time working and to cover all seven days of the week given all contact tracing should be done within one day for each case.

A fraction of health visitor (HV) and environmental health officer (EHO) staff can be redeployed initially to lead local teams of contact tracers to contact trace.[91] Most local authorities have established volunteer registers[92] and recently retired HVs and EHOs can also support the contact tracing effort. New staff will also need to be hired, given limited capacity and the existing important duties carried out by HVs and EHOs. The system of contact tracing could be up within weeks with sufficient political will and commitment. We assume that it will be possible for most Directors of Public Health alongside the Public Health Physician secondees from Public Health England to assess if they have control of the spread of the virus in their district a week later.

The incidence of new cases will vary between local authorities and regions (Table S5).

Initially the number of cases can be best estimated from local deaths. As the system gets underway, new cases can be notified in the standard way for notifiable diseases, for which testing is helpful but not necessary. The number of cases will fall as physical distancing succeeds, as in China. An estimated 800 to 1,000 contact tracers would be needed two weeks after peak deaths in the averaged-sized local authority (population ~375,000). We assume this is achievable, given the 750,000 people who have already volunteered to help the NHS tackle the pandemic.[93] Training is assumed to take one day, as is setting up the administrative arrangements using local authority resources. Testing facilities can be negotiated with the local health laboratory (see Testing section below). The local authority will be assumed to take on the public information function.

Community advisory committees and local health communication strategies

The overall success of this strategy rests on the willingness of citizens to engage with and accept the necessity of contact tracing and isolation for 14 symptom free days if in contact with a case, and of home testing via spit (saliva) samples. Social psychological literature suggests that health communication messaging and health interventions are most effective when anchored to meaningful dimensions of identity and personal experience,[94,95] which has been affirmed by evidence from previous epidemics including HIV[96,97] and Ebola.[98] Community-led and co-production approaches in the context of the COVID-19 response have been lacking,[99] but would be critical in ensuring that local engagement strategies result in significant uptake of testing, tracing and isolation over time. We therefore suggest that each local area develop a community advisory committee, whose role is to advise on the suitability of the national plan in their area, and to support the design of a local public health communications strategy tailored to specific subpopulations. It is critical that this group is composed of individuals from the full range of ethnic and cultural backgrounds within the area, given the importance of identity and context to the promotion of positive health behaviours, and the existing marginalisation of subgroups of the population. A life course approach would also ensure that any and all messaging was targeted to the specific needs and concerns facing individuals across the life course.

At the outset, community advisory committees may need to meet regularly (e.g. weekly to co-develop communication materials); but over time, its role could transition to helping provide an accountability loop between communities and implementer and managers of the TTI programme, which would require less regular contact. In this way, community members are able to feed details of emergent challenges and difficulties that people face in adhering to cycles of lockdown, real-time data on the efficacy of support systems, and ability to adhere to testing requirements over time. These groups could be coordinated by Public Health Covid supervisors (see below).

There are relevant concerns about how much time it would take to set up these groups in each area. However, each local entity will have a range of third and voluntary sector organisations who are already working to support various communities affected by the crisis. Rapid assessments and mapping of existing community networks by public health agencies would allow for a quick deployment of existing and active community groups in each area, to take control of recruiting relevant people from various backgrounds to engage with the committee.

The task of the supervisor will be to create an overarching structure to coordinate their efforts in a unified structure. In times of lockdown where participatory engagement is limited or restricted, evolving frameworks for how to conduct remote participatory research and community engagement could be adapted[100]. Such a community mechanism will have wide-reaching benefits, including; maintaining local buy-in over time, appropriately tailoring engagement strategies and innovating over time to maintain engagement, and helping citizens to feel as though they are a

part of a wider process for promoting collective wellbeing. The latter has been shown as critical in other crisis and recovery focused settings[101,102] and can have positive knock on effects for mental health outcomes in the general population, which is a growing concern in the crisis[103].

Contact tracing budget

One Public Health Community Officer (PHCO) will need to be recruited per 1,000 population (the exact number needed to be recruited in each 3 month block depends on the number of infections as explained in the economic model section), with budget for 20% extra posts included to cover sickness and absence to help ensure contact tracing always meets demand. These people should be familiar enough with their community to identify individuals disconnected from government reach and internet apps. They could be unemployed or under-employed lay people, including those made redundant due to the lockdown. No prior public health experience or skills will be required beyond minimal educational attainment and having been resident in their local area for at least a year, though ability to speak appropriate languages will be relevant for some communities. The PHCOs could be trained via a short online course delivered by public health professionals, and will undergo online refresher training every month. PHCOs will be paid a living wage of £10 per hour, £80 per day for an 8hr shift.

PHCOs will be supervised by full-time Public Health COVID-19 Supervisors (PHCS), at a ratio of 1 supervisor per 50 PHCOs. These PHCSs could be graduates of master's degrees in public health or related disciplines and appointed if they can pass a simple test about control of the COVID-19 epidemic in line with this strategy; or, if sufficient numbers are available and they would not be taken away from important existing duties, they could be Environmental Health Officers. They will be based in COVID-19 offices in their local authority area. Given 343 local authorities in the UK, each will have around 3 or 4 PHCS. PHCS will be paid £20 per hour, £160 per day.

Each local authority will need a COVID-19 response team lead overseeing this effort. The team lead will directly manage and supervise the PHCS and have an overview of the COVID-19 situation in their local authority area. They will be public health specialists with at least five years of experience, perhaps already in post in the local authority area. Importantly, their duties will only relate to the COVID-19 contact tracing, testing and isolation strategy. Therefore, if already in post they will be relieved of other public health duties (and an additional public health lead recruited to oversee such duties) – or perhaps less disruptively, individuals without existing duties will be recruited to lead the COVID-19 response in their local area.

The importance of an integrated system with all workers solely focusing on COVID-19 needs to be emphasised. It is likely to be necessary to ensure the consistently high levels of contact tracing, testing and isolation required (see following section for rationale for coverage levels).

Mobile phone costs and travel costs are included for all cadres as needed.

2. Testing – SARS-Cov-2 viral RNA RT LAMP tests to detect active infection via home saliva samples

A population-wide testing programme[8] is a core component of PTTI. This would require the following resources, which are either currently available or can be sourced from UK suppliers within a matter of weeks:

1. A register of names, dates of birth, and addresses of all residents registered with a GP, to be updated as necessary with test results, changes of address and addition of unregistered subjects. Anonymous registration with local outlets for sample collection and delivery is needed for those reluctant to give name and address. "Ghost patients"[104] can be dealt with using the strategy developed by the ONS.

2. New 96-well PCR machines running direct RT LAMP assays[105] 18hrs per day processing 96 samples every 30 minutes. Experienced staff to operate them are already in place in large and small academic and commercial labs throughout the UK, including possible demonstration sites. Posts for four 9-hour shifts for lab workers will be needed: 1 technician running each machine and 1 filling the wells with samples.

3. Self-sample spit (saliva) test kits including sample transport tubes individually labelled with name, date of birth, and barcoded ID, PCR reagents (note RT LAMP does not require the RNA extraction step so needs less reagents), and microtiter plates for 10 million tests per day. Additional production facilities must be commissioned if necessary (Box 2).

4. Arrangements to deliver and collect samples from every household once a week, with delivery to a testing lab within a few hours. Results would be directly uploaded online automatically by the RT LAMP machine into a LIMS system as the sample is diagnosed by the machine, coupled with autotexting of negative results using software already in place. Positive results in those without phone or email would be delivered by courier.

5. This high throughput would depend on various regulatory emergency waivers:
    a. Lab staff would wear PPE where necessary but would not be accredited to conduct medical tests.
    b. Laboratories would be advised on precautions but not accredited for handling infectious samples.
    c. PCR reagent production with normal non-medical quality control cannot be hampered by patents or regulations on medical test manufacture.

We recommend evaluation of regular COVID-19 saliva testing of the whole population in an entire city as a demonstration site (preferably several towns and cities), with strict household quarantine following a positive test. Quarantine ends when all residents test negative at the same time. Everyone else can resume normal life if they choose to. This should be assessed for feasibility in one or more cities with populations of 200,000–300,000. This experiment could only be achieved after extensive, transparent public engagement leading to widespread public acceptability across all social and economic groups. Economic and educational measures would need to be provided to ensure equity with the non quarantined population. Although this is an ambitious proposal, it does need to begin as soon as possible, whilst the infection rate is fairly low but rising. The rate at which it then rises or falls compared with the rest of the UK will be apparent within a few weeks. A decision can then be taken on national roll-out, beginning in high-risk areas.

A local population of 200,000 with 90% compliance will require 26,000 tests per day, plus an excess to offer more regular testing for NHS staff and care workers. Whatever the results, these data will enable policy to be based on real-time evidence (instead of modelling assumptions) on new infection rates in the expanding regularly-tested population and the untested remainder. The latter can be monitored by testing population samples as well as by NHS number linkage to hospital diagnoses and GP records. Complementary aspects of PTTI: contact tracing and phone apps will be critical in the unscreened population, and may enable testing to be done less frequently as prevalence falls. Testing would be voluntary, but incentives for staying in quarantine following a positive test in a household could be considered in line with those suggested by community advisory committees. Helplines would be provided to support quarantined households with access to income compensation, mental health support and food delivery.

These pilot studies will show whether PTTI is a practicable way of responding to the COVID-19 epidemic. Even if the epidemic is not completely controlled in pilot studies the establishment of far greater testing and tracing capacity will facilitate other initiatives. Different households would return samples on different days, giving a daily sample of each small area. Depending on the proportion of people tested and cases detected a local outbreak could therefore be detected soon after it occurs, as test results would be automatically uploaded online by each PCR RT LAMP machine.

A register of everyone registered with a GP (suitably amended to deal with unregistered people and “ghost patients”) would be used to deliver and collect saliva (and nasal/throat in a subsample) self-samplers in bar-coded tubes labelled with name and date of birth of all residents to every household once a week. The register would be expanded to include any missing people who are subsequently identified (with unique ID numbers for those with no NHS number) and continuously updated to assign people to the household of their current address. Many “households” would have one resident.

Households would self-isolate on the day that any resident gets a positive test, with earlier self-isolation of a household when anyone in it is thought to have COVID-19 based on a publicised list of diagnostic symptoms, pending the household’s next test results.

Contact tracing (above) could be focused on the “hard to reach” population that the uncontrolled epidemic will then be confined to. Anyone not possessing a negative test result dated in the past week would be required to provide a saliva/nasal/throat sample and their name, address and date of birth. They would be added to the register and sent weekly self-sample kits like everyone else. There will be challenges with this, for example, inclusion of the homeless population, that may need to be overcome.

Samples would be analysed on PCR machines in university and commercial labs, if necessary by continuous (24-hour) operation (with very occasional down-time for maintenance), though we have costed 18hr per day operation. Laboratory and testing regulations would have to be set aside to enable the laboratory staff currently using these machines for other purposes to do the testing supported by additional assistants. Strategic planning to identify essential laboratory work that needs to be continued during the COVID-19 crisis will be required. This should consider the opportunity costs of not doing such work, whilst also considering the opportunities and costs of extra shifts to utilise the same equipment, recruitment and training of extra lab staff and potential efficiency gains to existing processes (including those that could be gained via relaxing regulations, along with the potential costs of relaxing such regulations).

One of the key bottlenecks for ramping up testing to such a large scale is the availability of reagents and test kit supplies for the tests. Creative ways of resolving this issue are urgently needed (Box 2).

Box 2: Sourcing reagents and supplies to scale up to millions of tests a day

This is very ambitious compared to the number of tests currently conducted each day. However, it is in line with international estimates of the scale of testing required.[9,10] The UK government's five-pillar plan for scaling up COVID-19 testing[106] reaches out to local manufacturers to ramp up testing capability and pharmaceutical companies are also offering to help.[107] The extent to which such capacity can be transformed into delivery of the government's current target of 200,000 swab and antibody tests per day is still unclear, hence our modelling of more conservative scenarios as well.

Studies are underway to confirm that saliva samples collected into simple specimen pots can reliably be used for mass population SARS-CoV-2 testing; if confirmed this would remove the current bottleneck in swab availability. The main testing reagents in short supply are not likely to be the non-biological chemicals used, large enough quantities of which could fairly easily be produced in around 3 months by industrial chemical companies. Some of these materials are already supplied by large companies such as BASF. The bespoke formulations of the mixtures of bio-based reagents, such as proprietary mastermixes and primers specific to each test kit, are potentially the main bottlenecks[108]. It will likely be easier and quicker for the existing manufacturers to scale up production than for a new company to attempt to do so, as the new company will require all of the same ingredients in order to exactly match the bespoke formulation of the specific test kit.

Therefore, the UK government probably needs to coordinate industrial consortia of companies with relevant scale-up capabilities and Good Manufacturing Practice approval, such as Robinson brothers[109] (based in the midlands), and test kit manufacturers, such as New England Biolabs and OptiGene to ensure there is adequate supply of key reagents. In this way, test kit manufacturers will be enabled to create the quantities of the bespoke proprietary formulations needed for millions of tests a day in the UK.

To ensure manufacturers have adequate incentive to participate, the government could issue "put options" that allow the companies to recoup most of their losses in the event the kits are never used[110]. More traditional methods of reducing commercial risk, such as direct purchase orders and public-private partnerships, can also be considered so long as they can be arranged quickly enough.

Initial estimates from an industrial chemist suggest the costs to cover the UK demand, per type of reagent, are on the order of £5-10m. It would require short bespoke use of manufacturing units (equipment) per component, the blending of the final formulation, and finally the development of appropriate logistics. The total cost is estimated to be less than £100m.

Rapid efforts will also be needed to source the swabs required to collect nasal/throat self-samplers and the bar-coded tubes labelled with name and date of birth of all residents, to deliver to every household once a week. Again, option-based guarantees and other de-risking measures could play an important role in ensuring the demand is met[110].

3. Isolation Support and Enforcement

The team of PHCO and PHCS will follow up all those who test SARS-CoV-2 positive and who therefore require isolation. They will ensure that the people requiring isolation understand they need to stay at home for the required period in order to not spread the virus, and steps will be taken to ensure that households have the resources necessary to comply with isolation in the first instance. The costs of policing any infringements will be met by the fines levied for such infringements (likely with surplus funds left over). Therefore no costs are added for isolation encouragement and enforcement.

For isolation support and enforcement to work without disadvantaging marginalised groups further the following will need to be put in place:

1) financial compensation for time off work to comply with a 14 day isolation order following tracing;
2) clear guidelines on the roles and powers that police and other authorities have in enforcing isolation;
3) a means-based fine system for infringements of isolation, based on household income levels/earnings;
4) development of minimum packages of support that are streamlined to specific vulnerable populations – so support that is provided is bespoke for the needs of each household during an isolation period (i.e houses where earning levels are not impacted will be offered a different resource package than those where earnings are impacted);
5) assurances that basic resources (heating, water, electricity, internet access) will be guaranteed during the period of isolation, and for a one month period post isolation.

On rare instances where households still break isolation rules, police officers will be put in touch with households in breach of guidelines. Fines will be levied in line with household income levels (there is precedence for this with speeding fines[111]).

Supplementary Results - Scenario trajectories

Figure S1 Scenario 1 trajectory

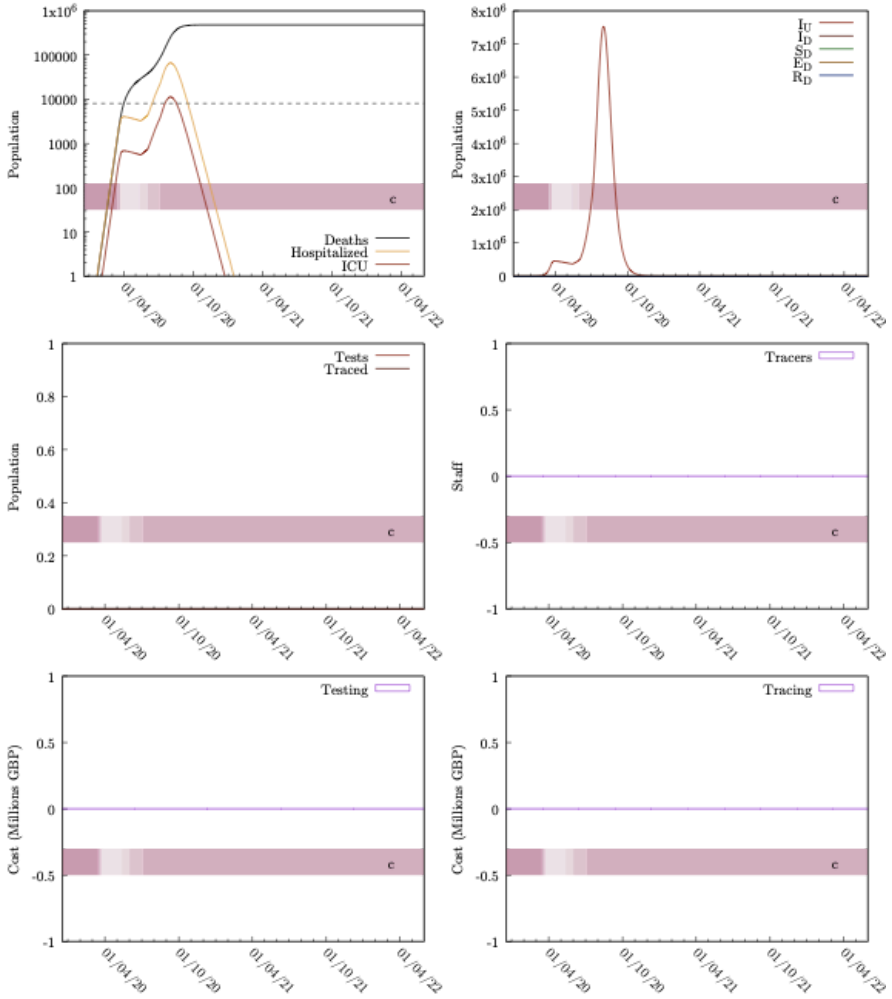


Figure S2 Scenario 1-Trig trajectory

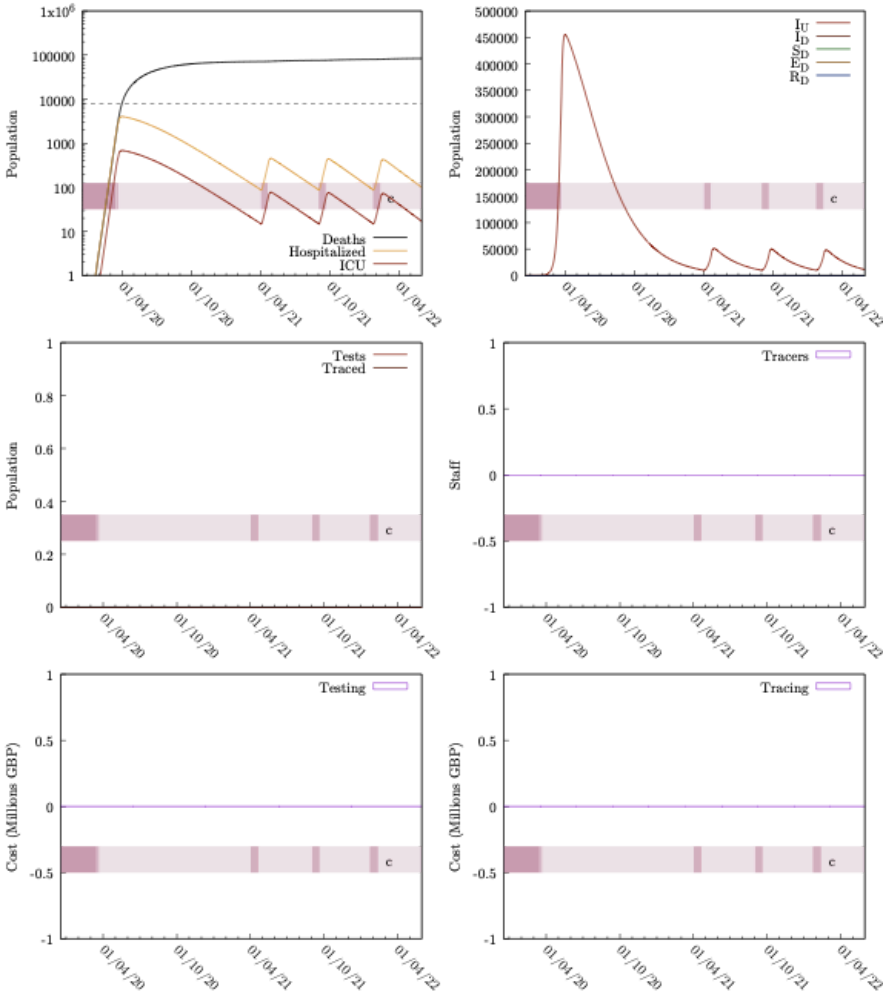


Figure S3 Scenario 2a trajectory

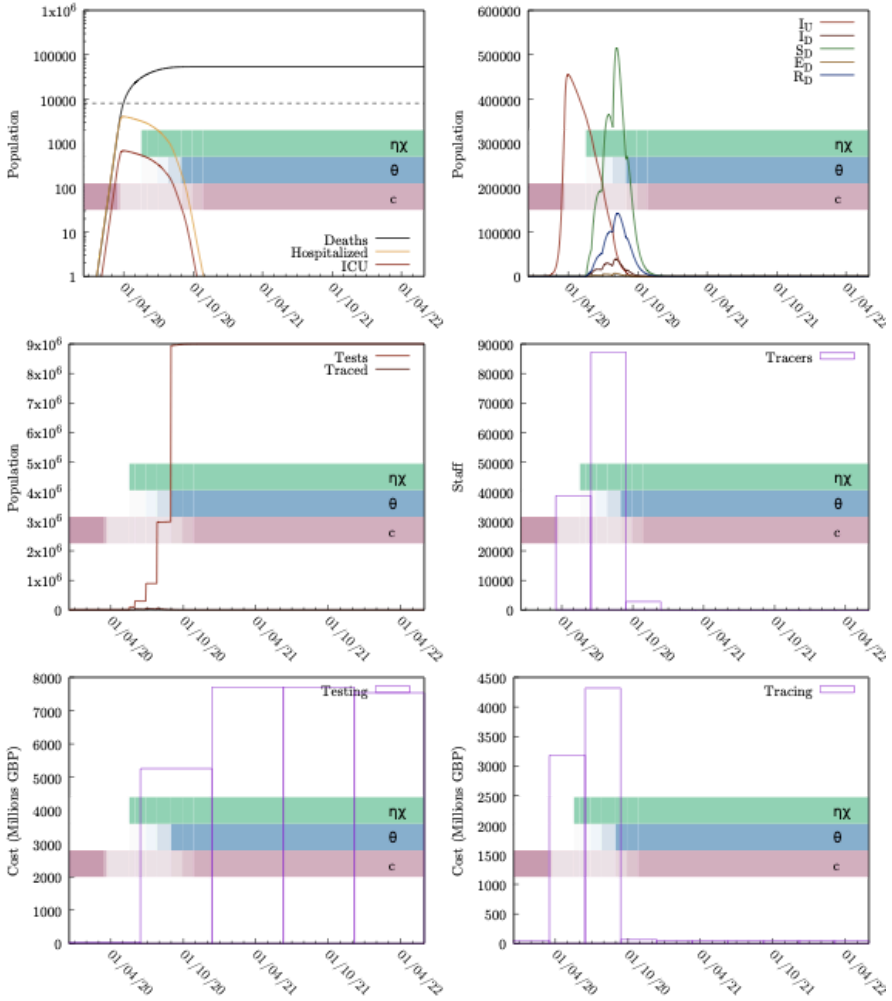


Figure S4 Scenario 2a-Trig trajectory

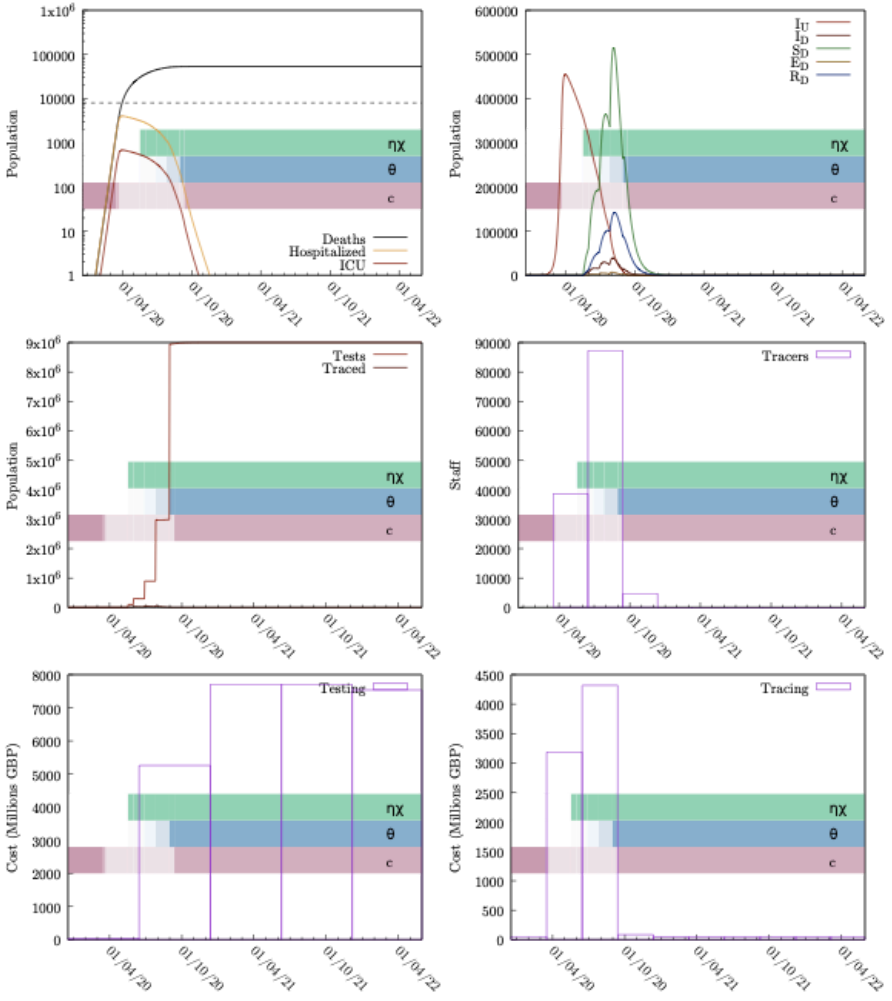


Figure S5 Scenario 2b trajectory

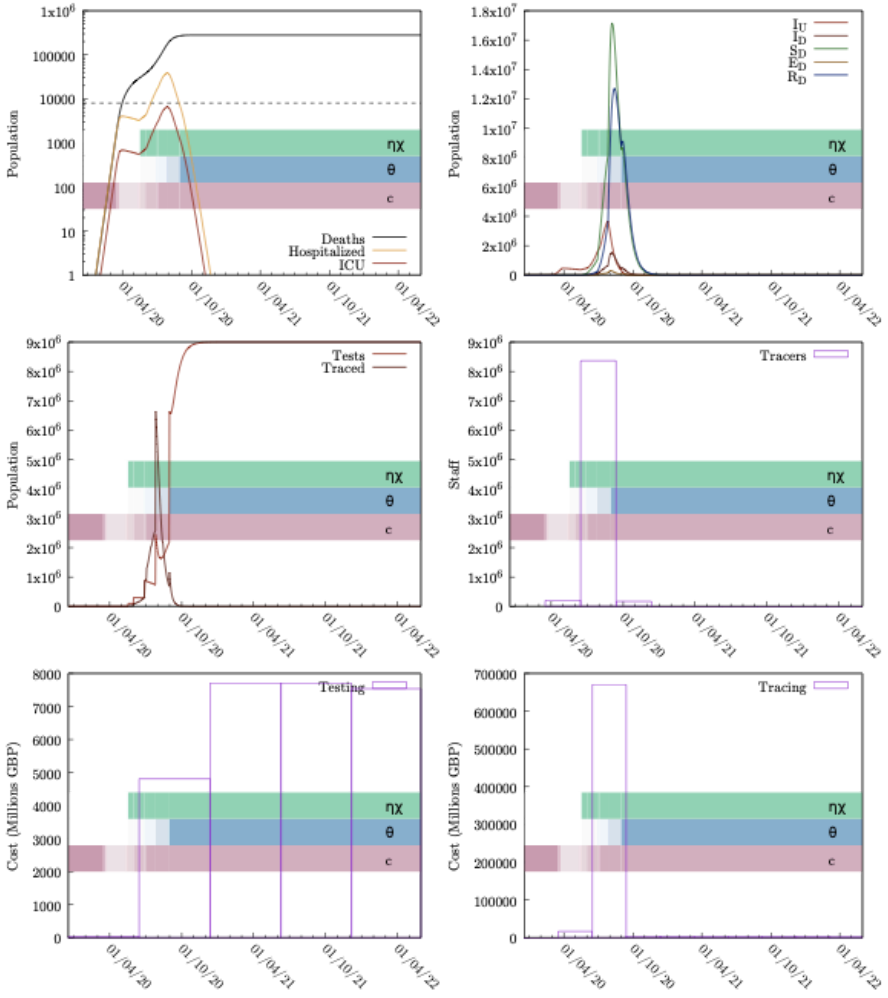


Figure S6 Scenario 2b-Trig trajectory

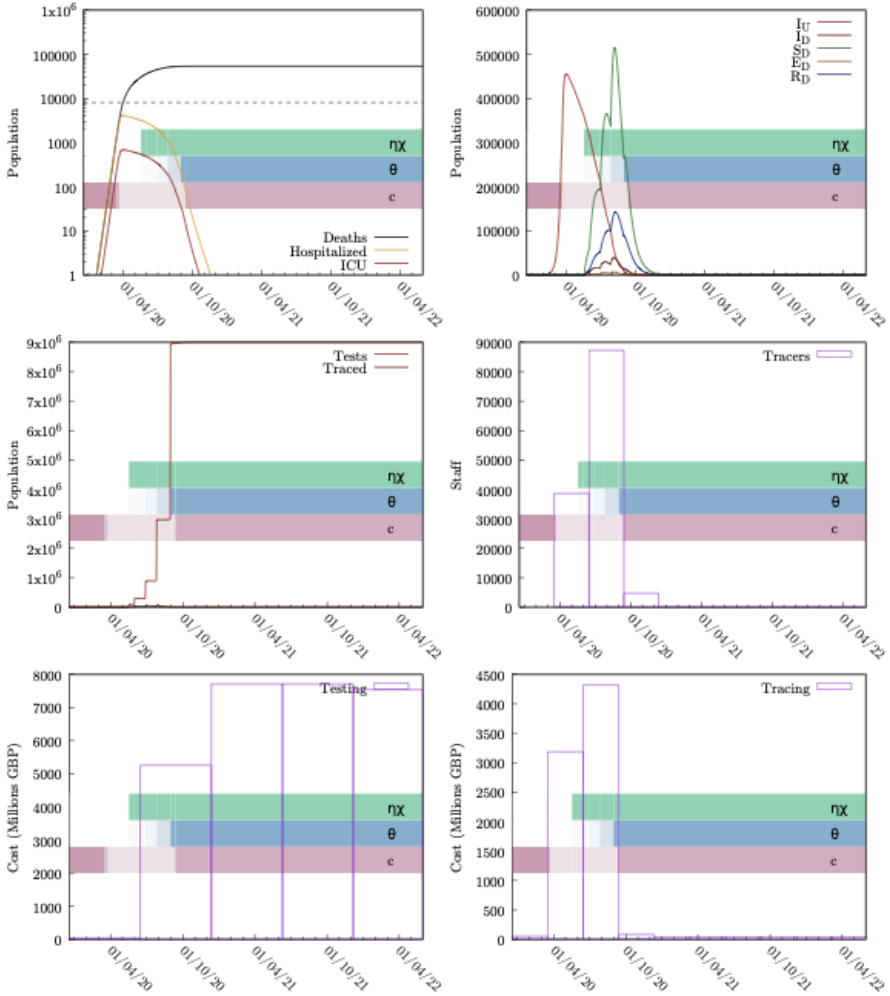


Figure S7 Scenario 3a trajectory

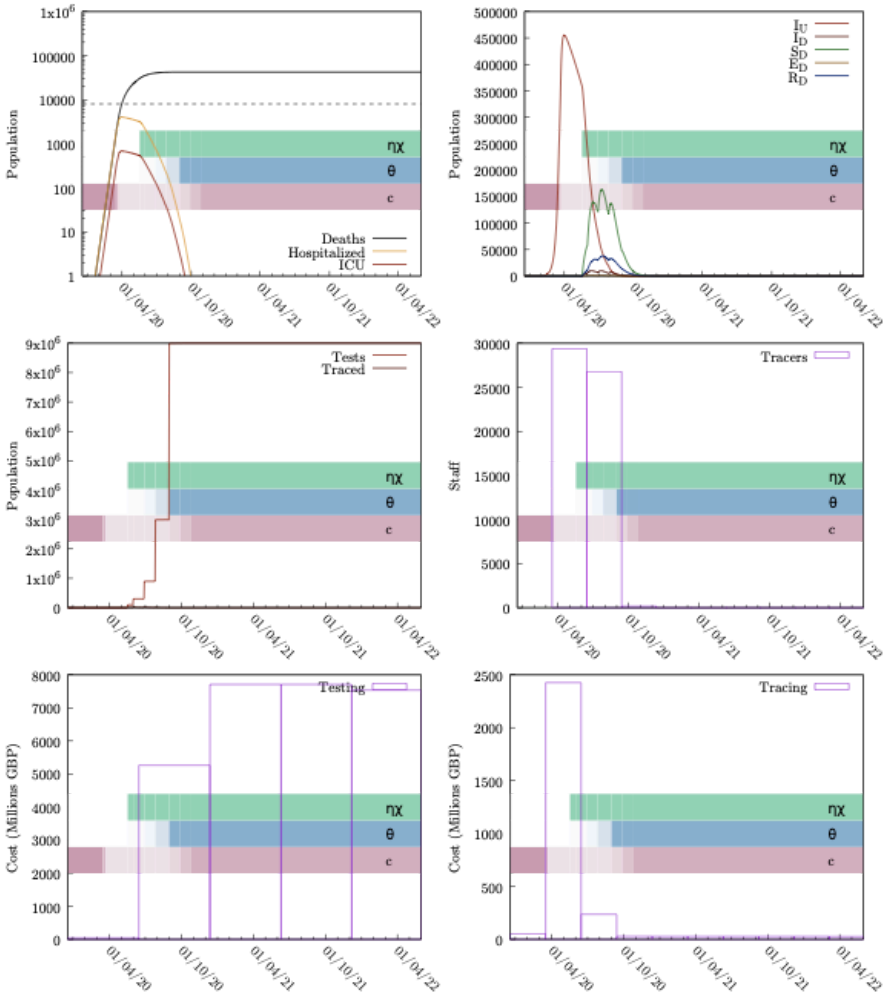


Figure S8 Scenario 3a-Trig trajectory

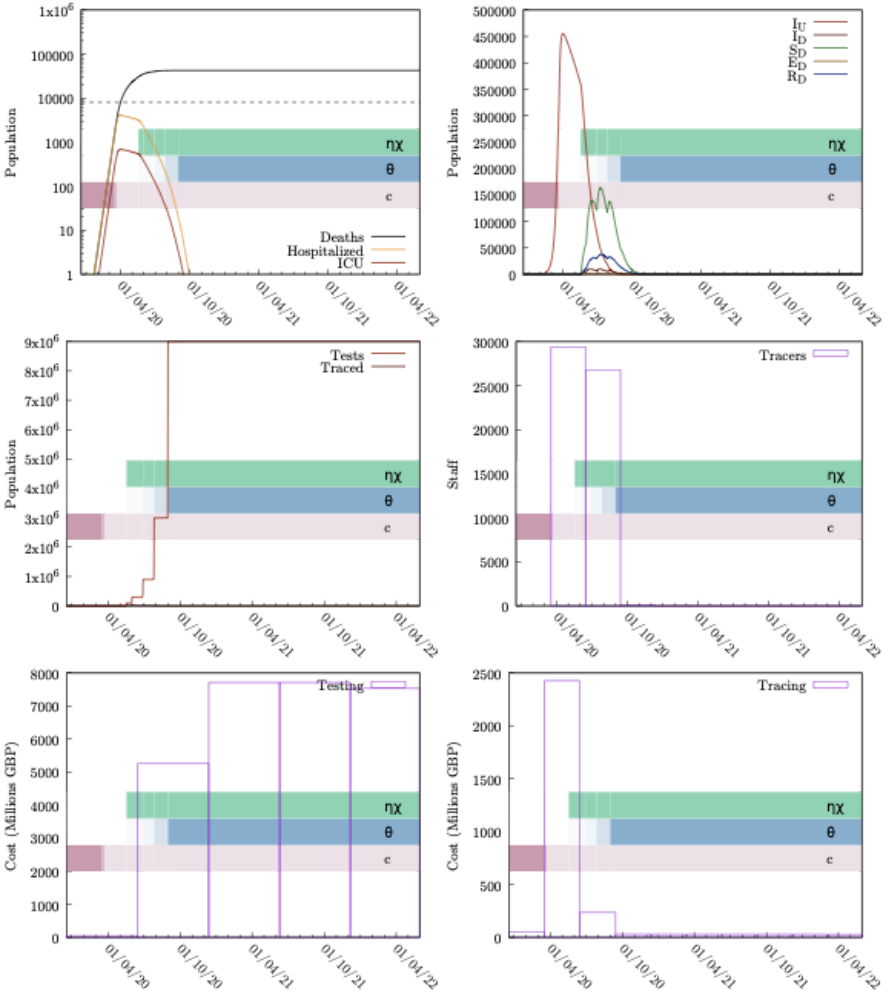


Figure S9 Scenario 3b trajectory

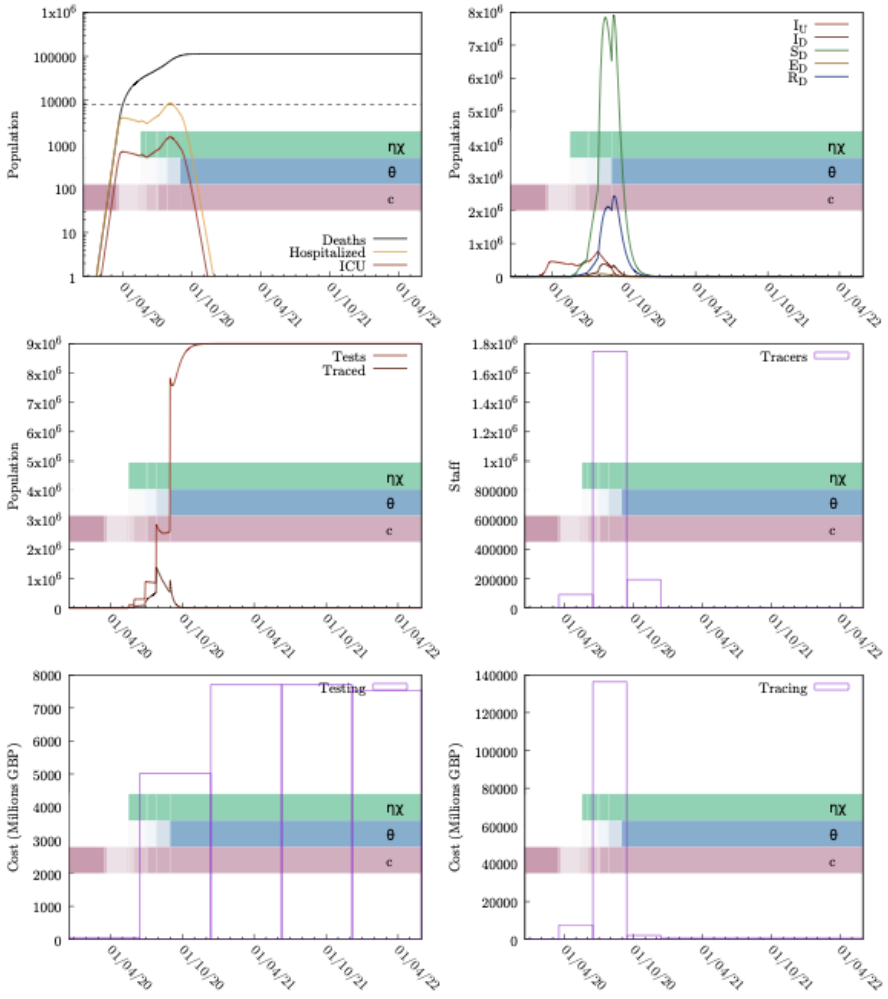


Figure S10 Scenario 3b-Trig trajectory

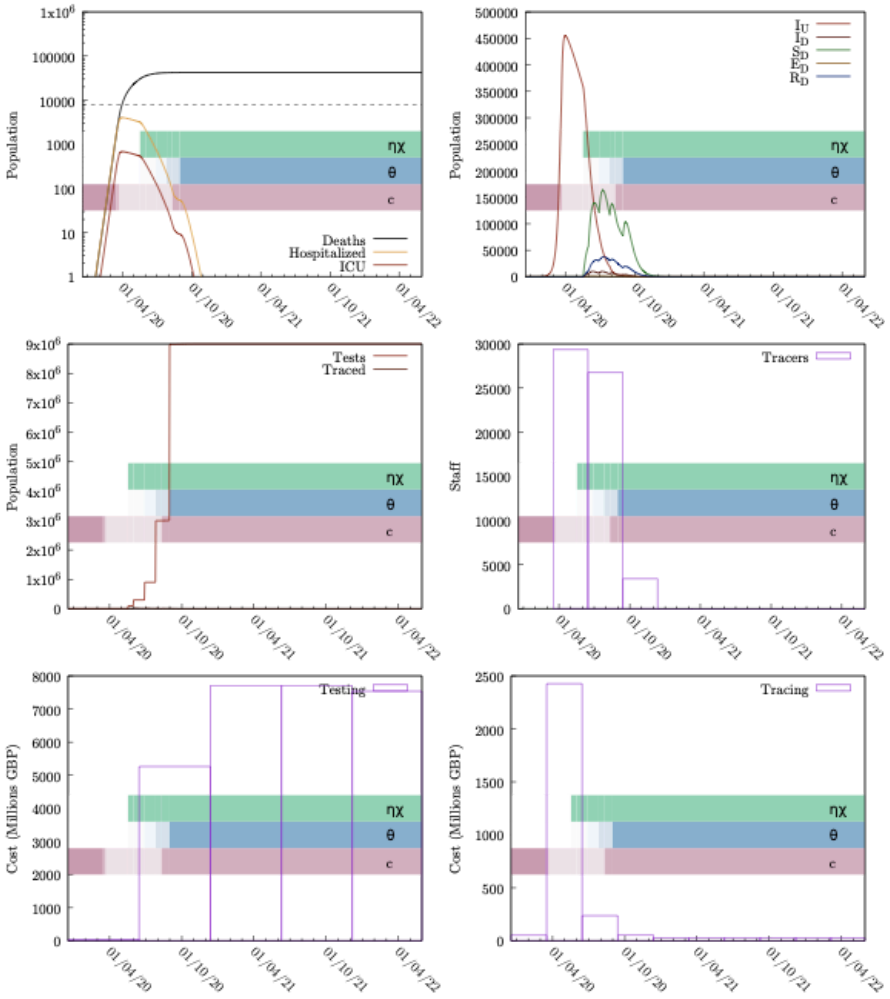


Figure S11 Scenario 4a trajectory

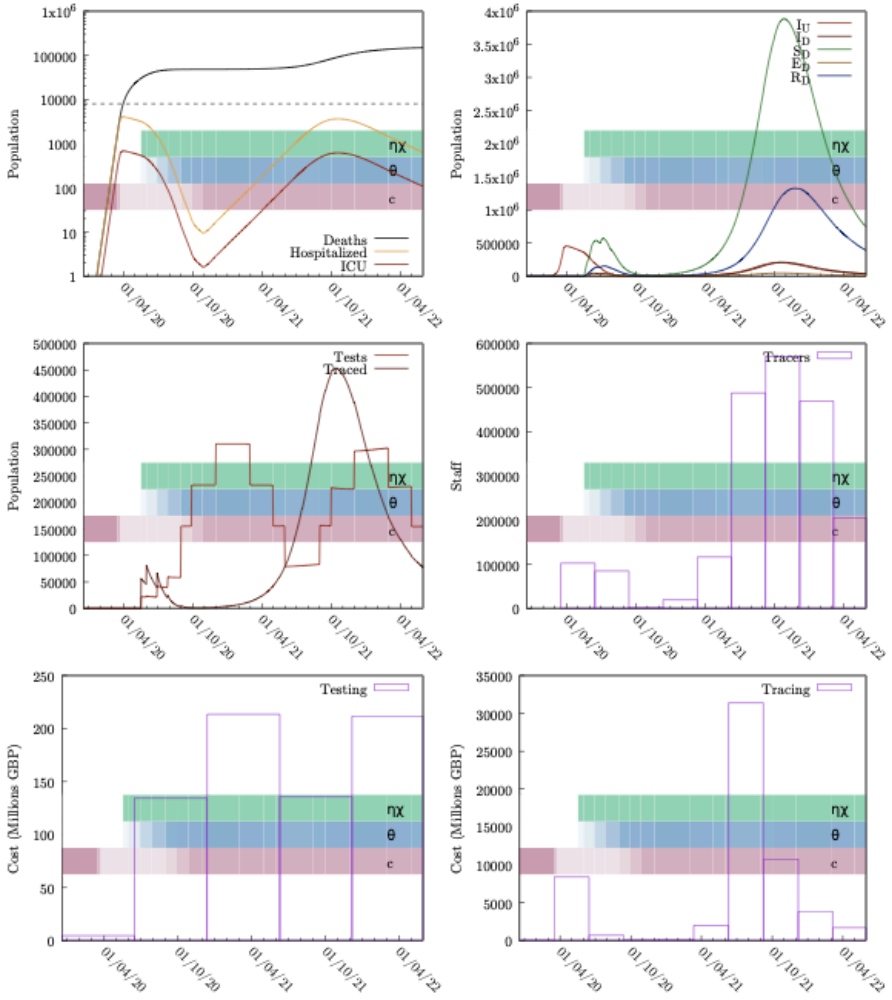


Figure S12 Scenario 4a-Trig trajectory

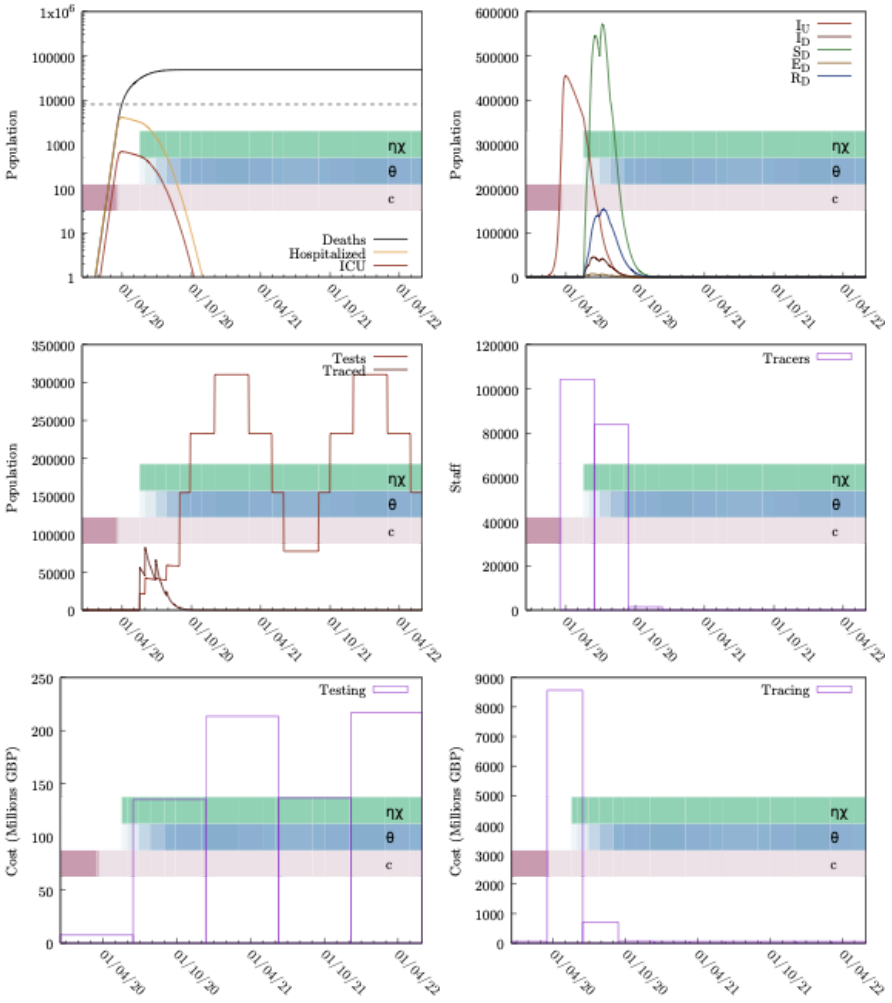


Figure S13 Scenario 4b trajectory

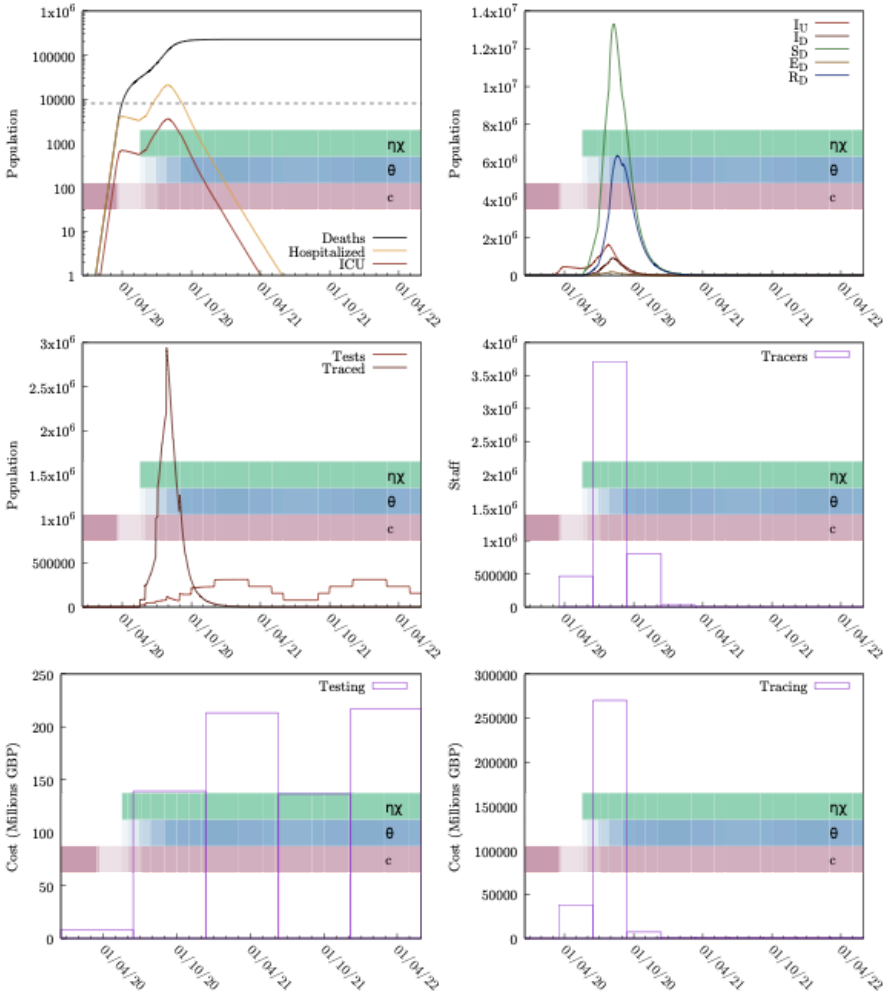


Figure S14 Scenario 4b-Trig trajectory

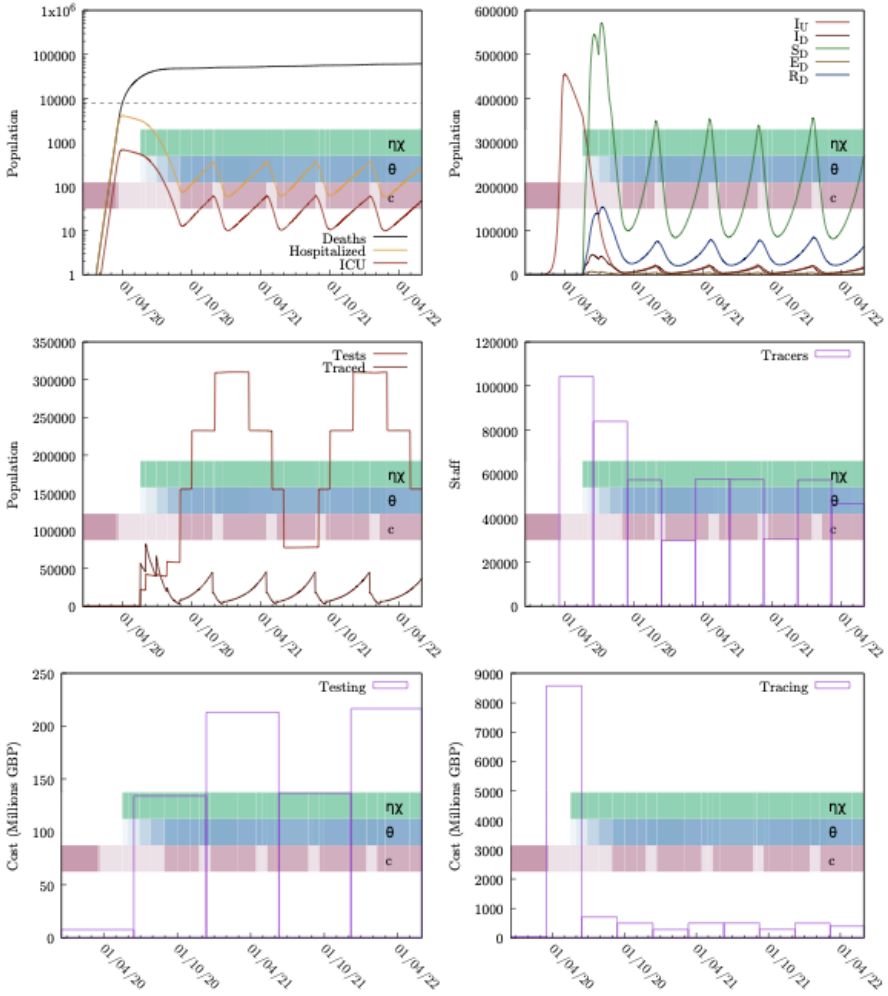


Figure S15 Scenario 4c trajectory

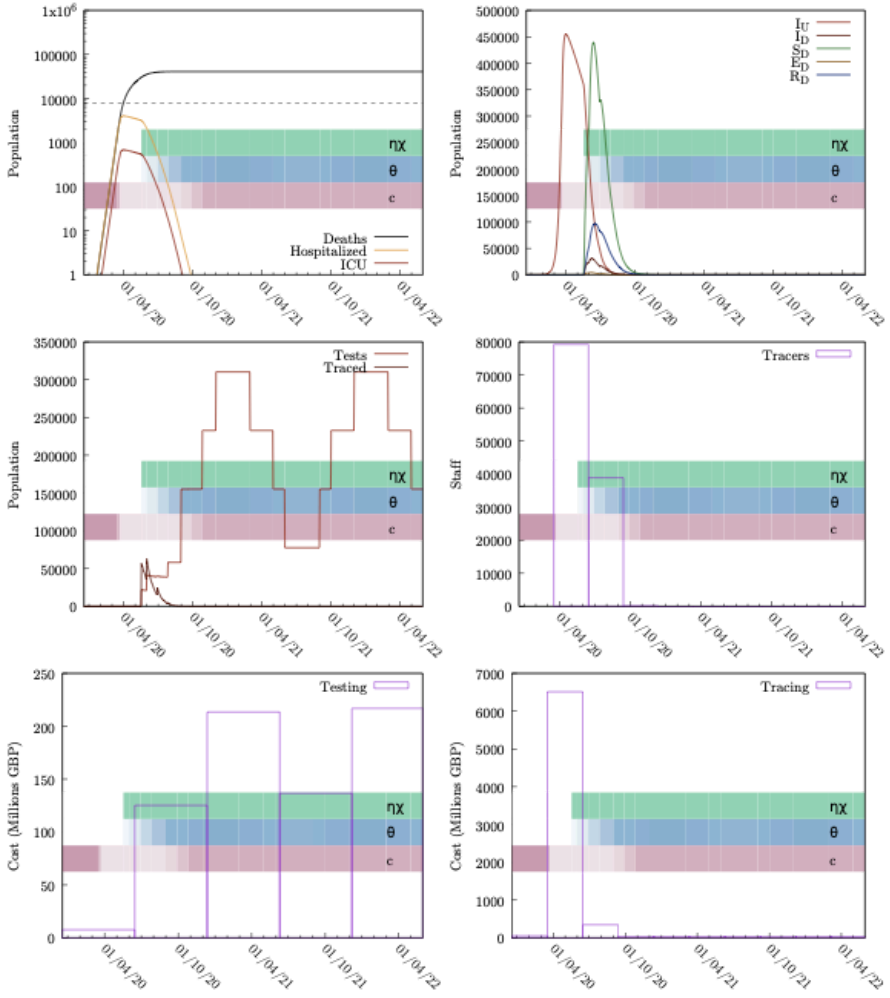


Figure S16 Scenario 4c-Trig trajectory

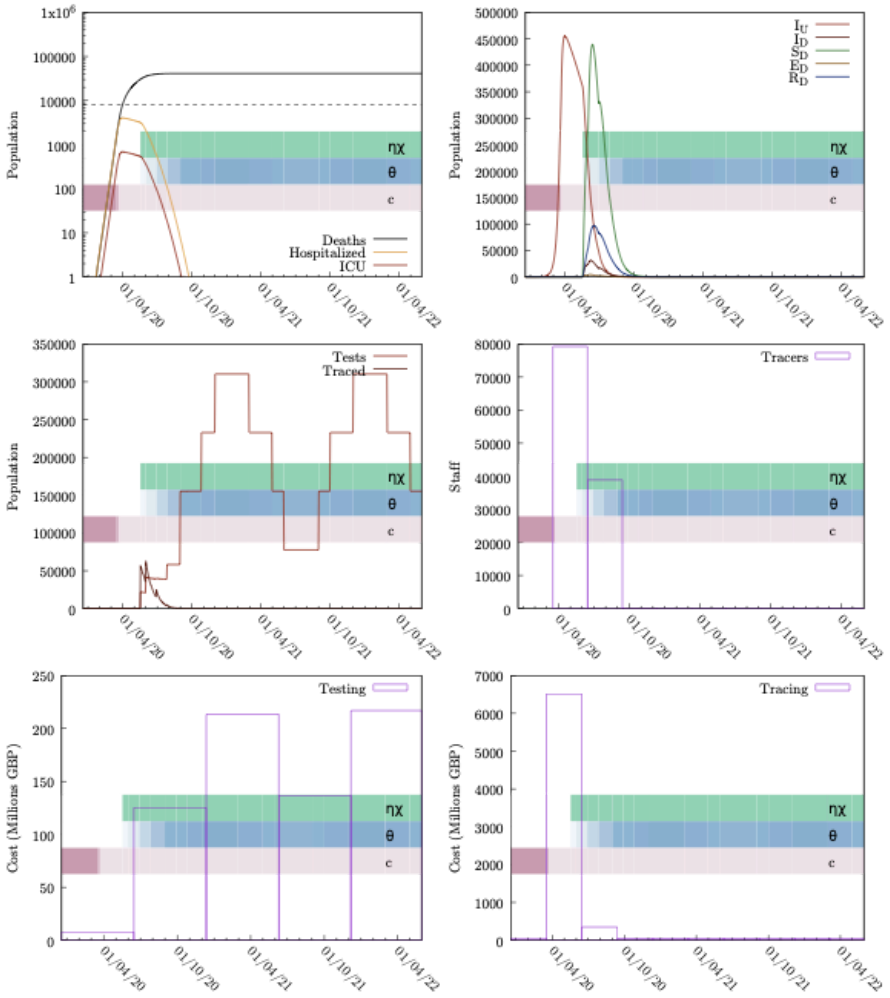


Figure S17 Scenario 4d trajectory

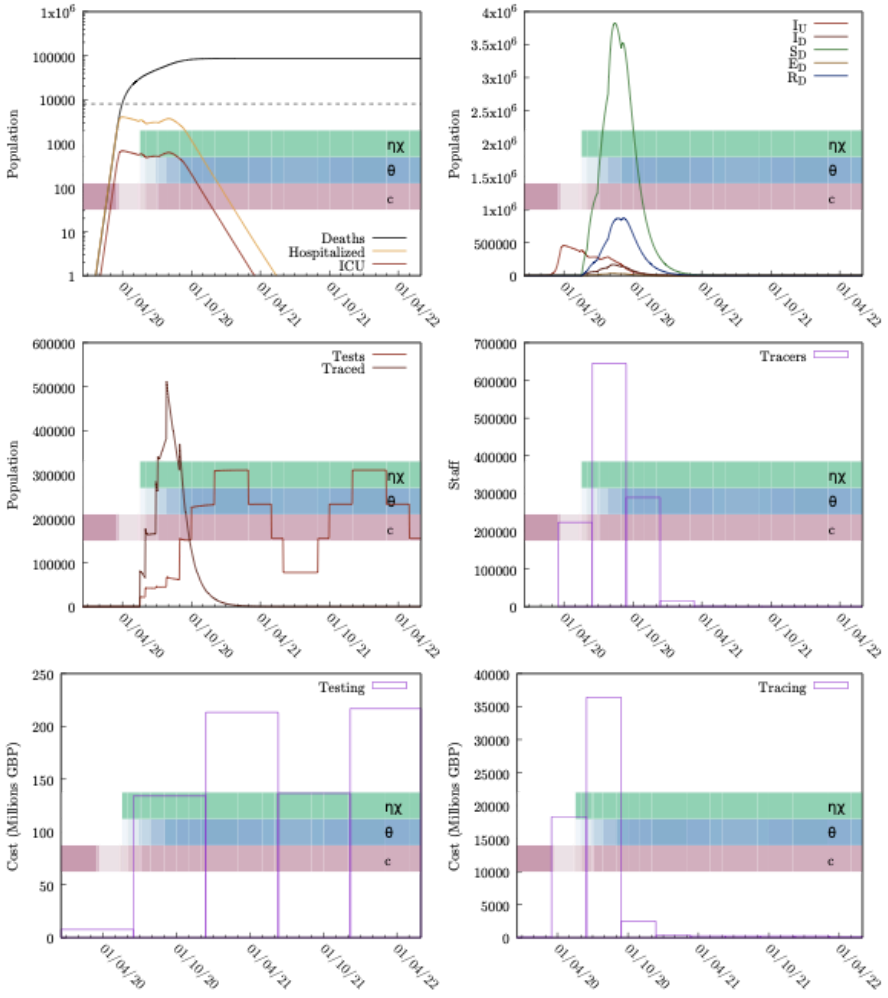


Figure S18 Scenario 4d-Trig (80% traced) trajectory

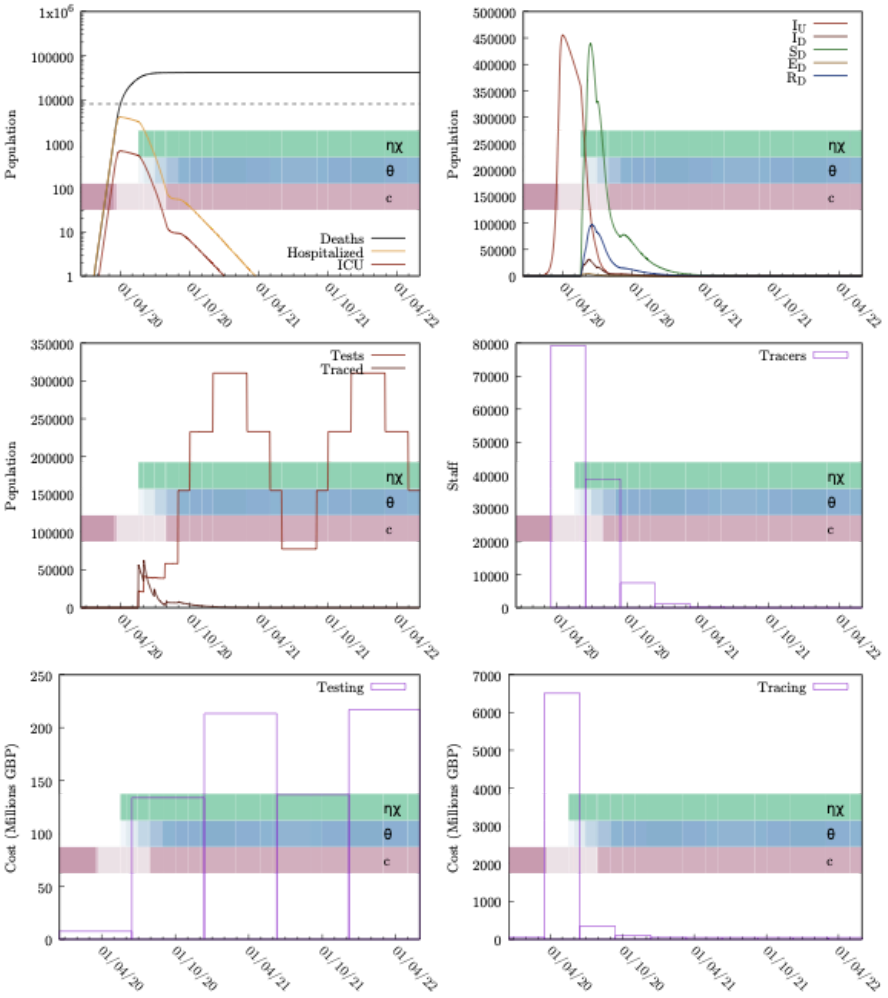


Figure S19 Scenario 3b-Trig 0% traced trajectory

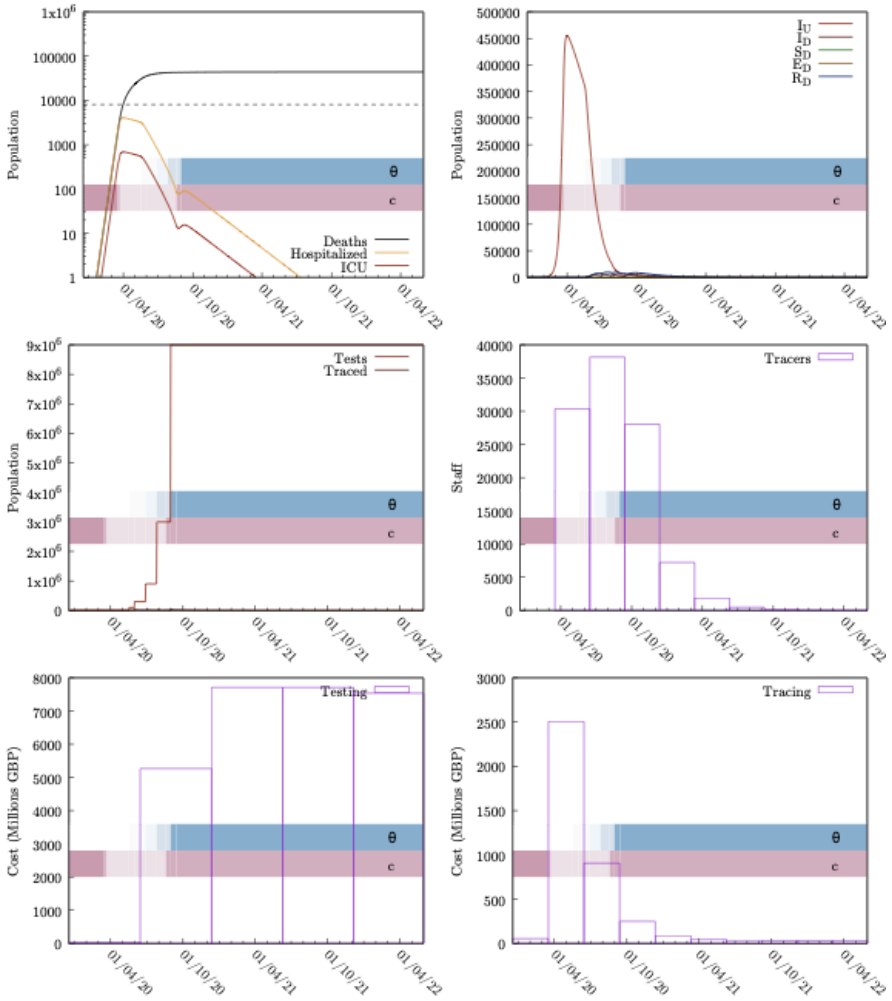


Figure S20 Scenario 3b-Trig 10% traced trajectory

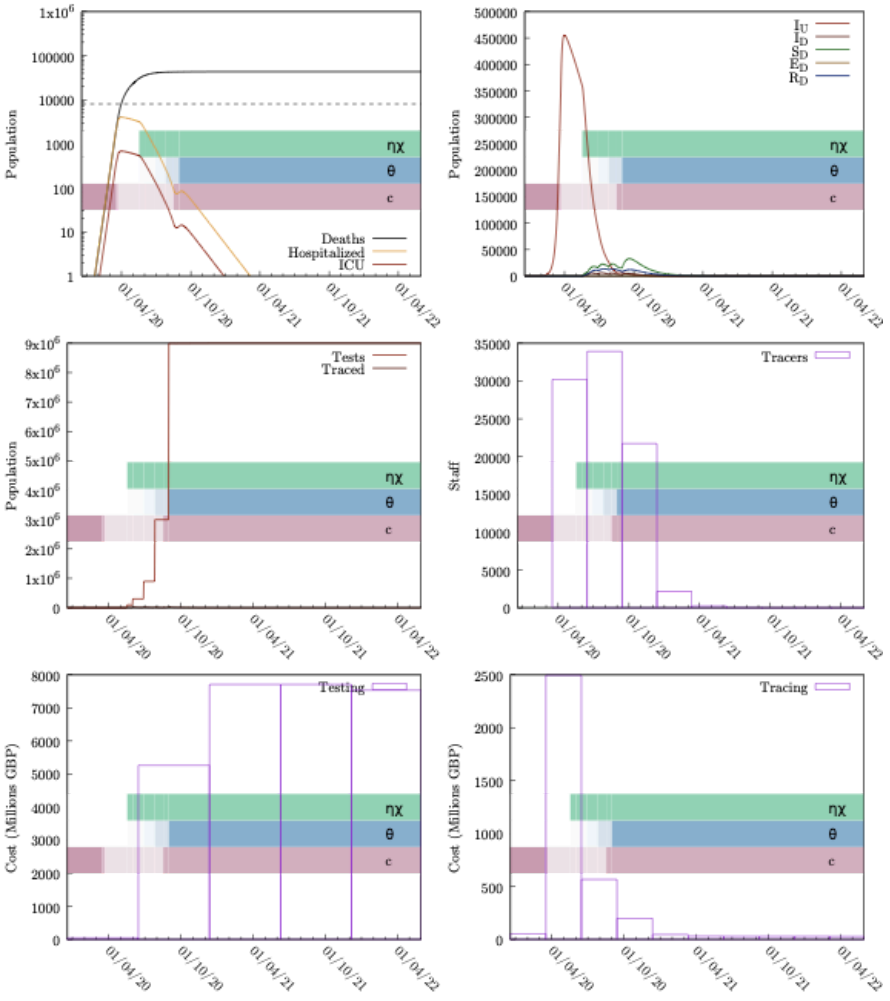


Figure S21 Scenario 3b-Trig 20% traced trajectory

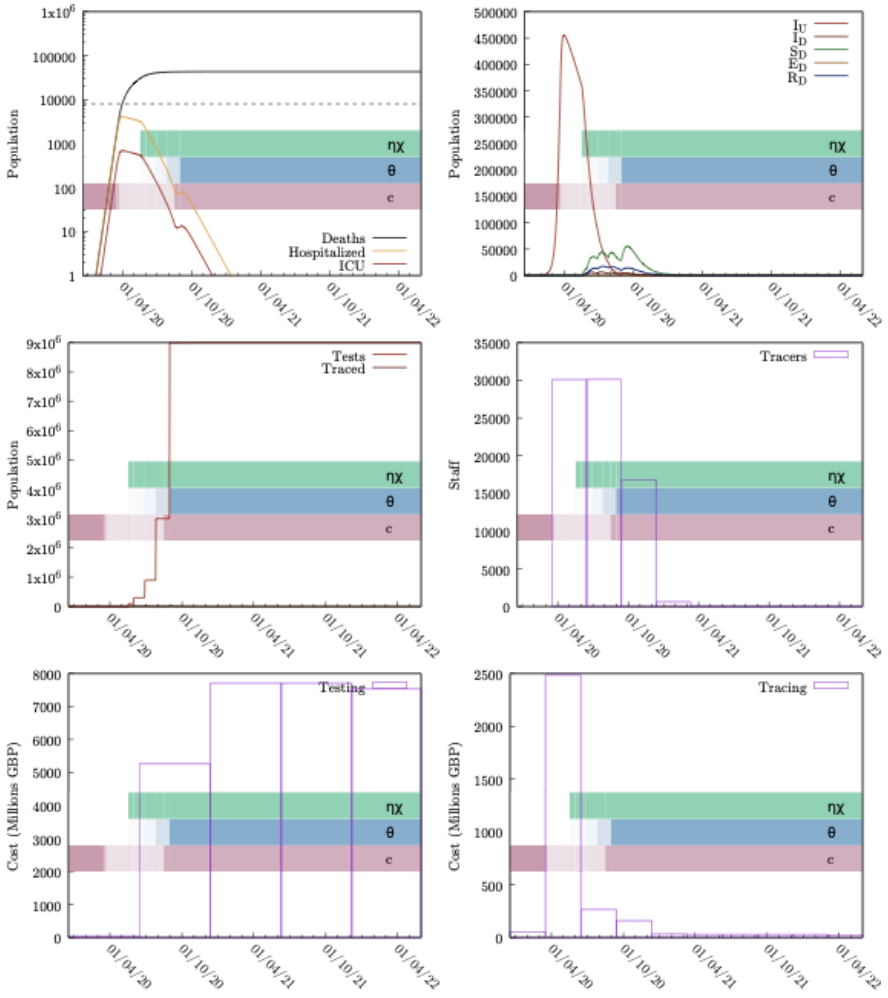


Figure S22 Scenario 3b-Trig 30% traced trajectory

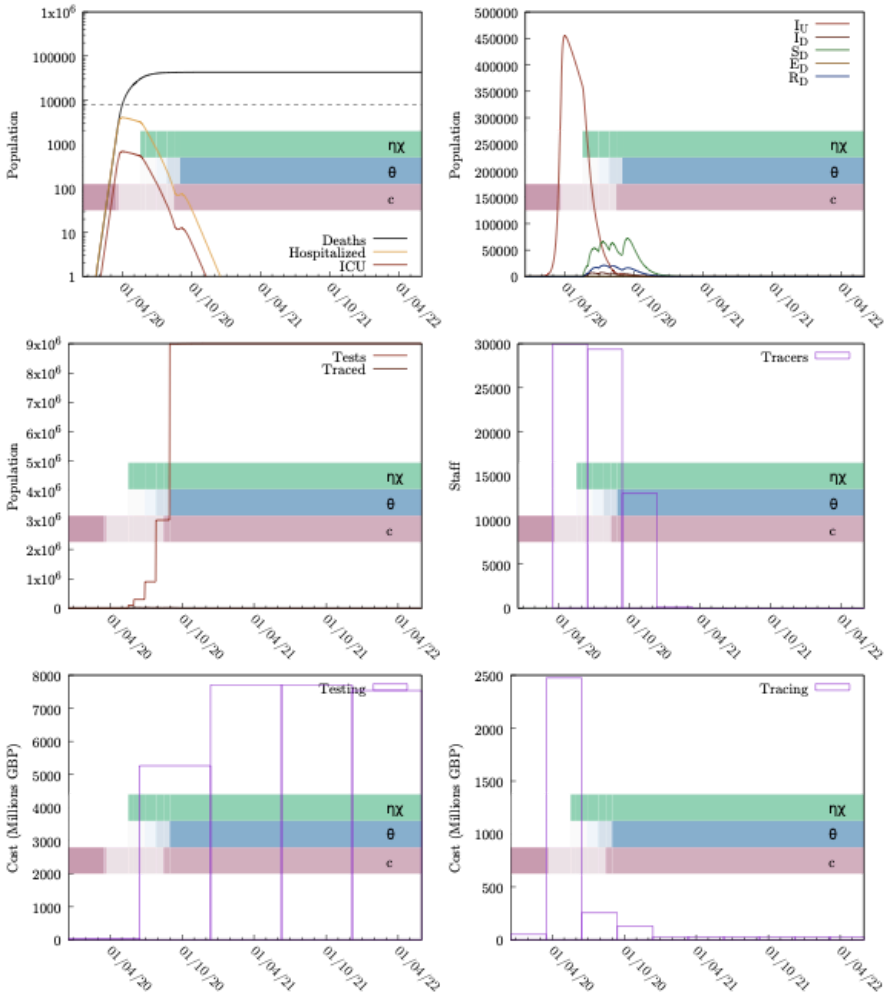


Figure S23 Scenario 3b-Trig 2 months 0% traced trajectory

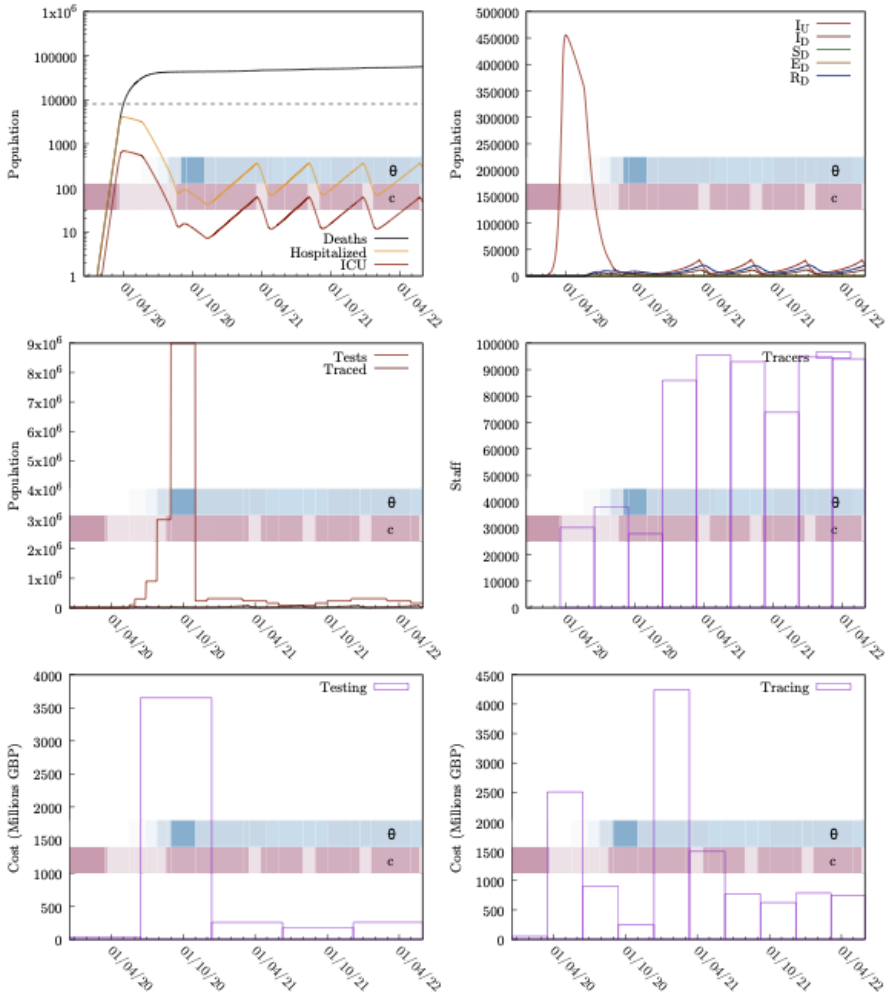


Figure S24 Scenario 3b-Trig 2 months 30% traced trajectory

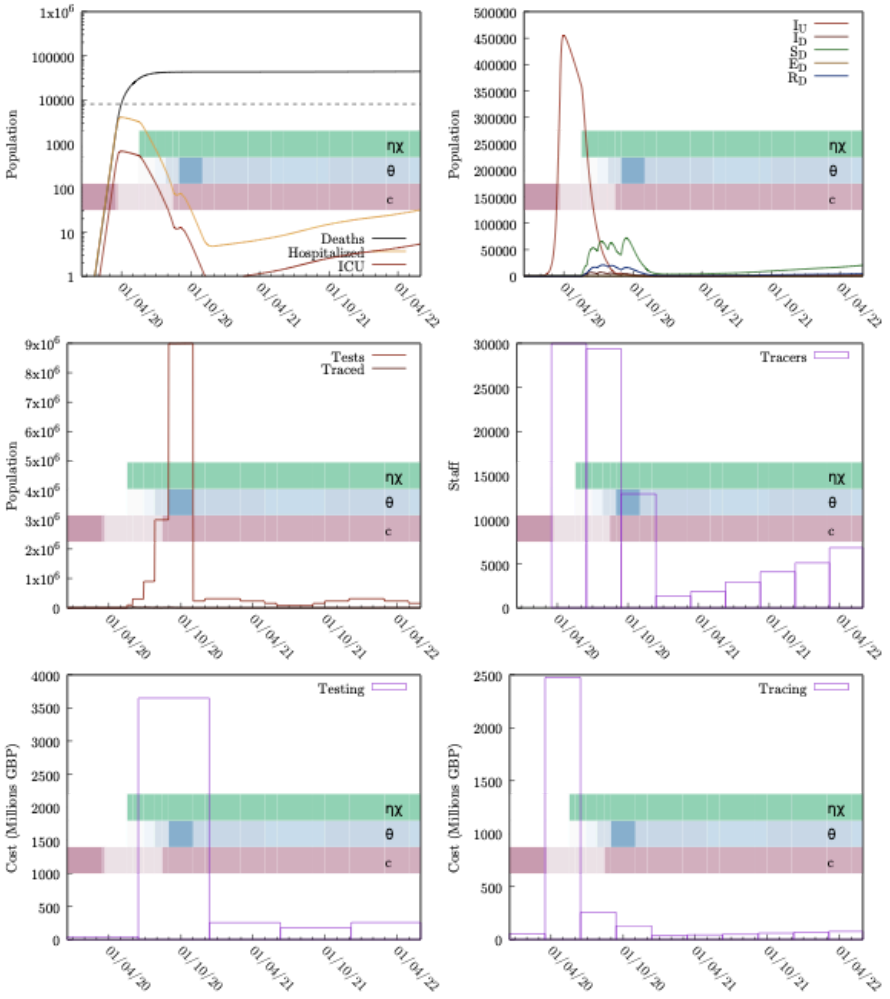


Figure S25 Scenario 4d-Trig 10% traced trajectory

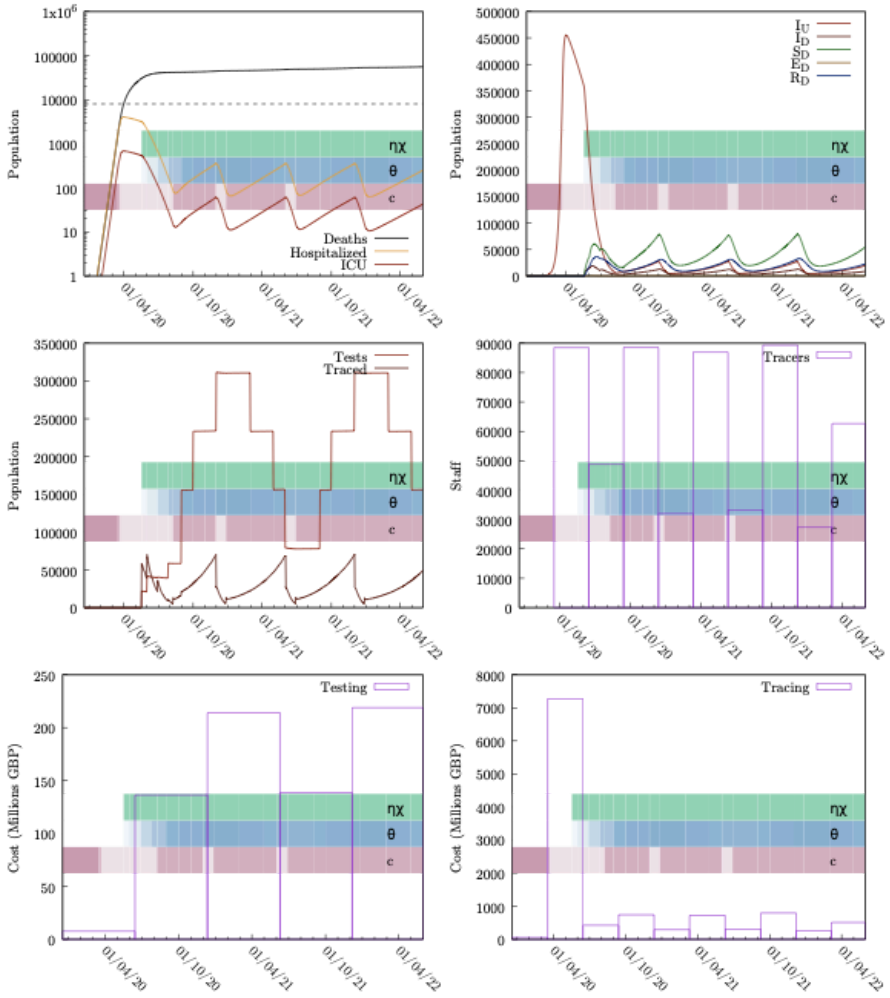


Figure S26 Scenario 4d-Trig 20% traced trajectory

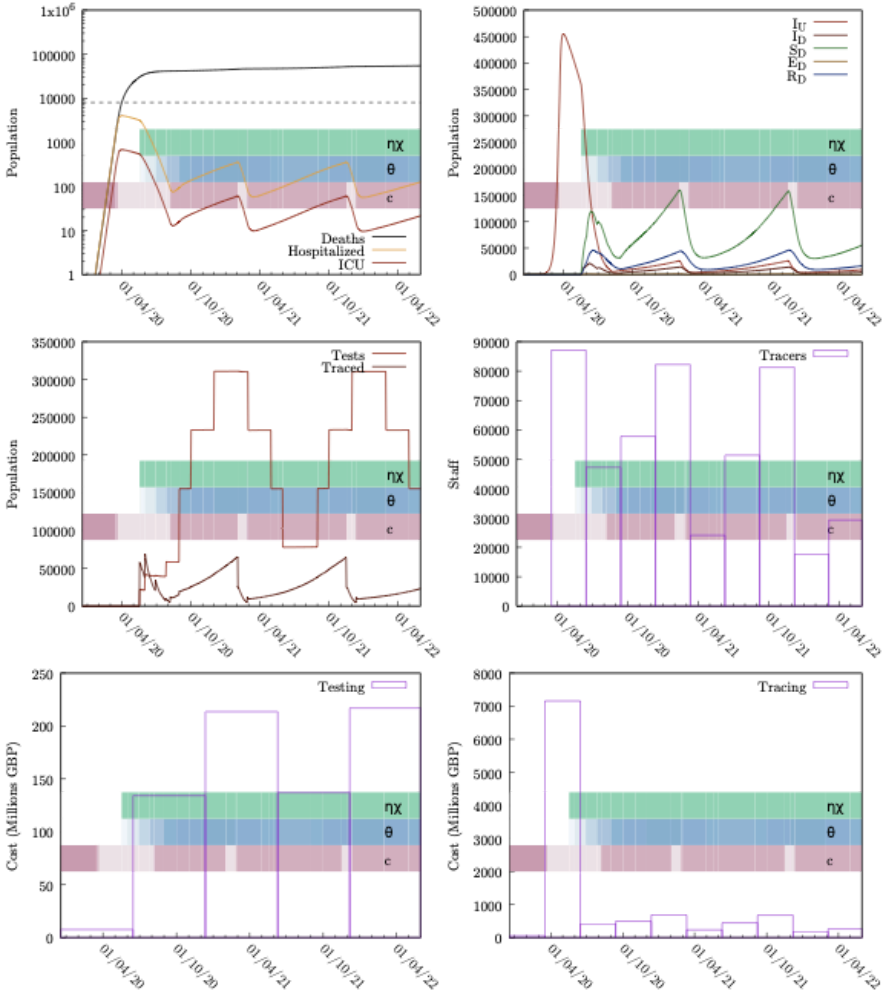


Figure S27 Scenario 4d-Trig 30% traced trajectory

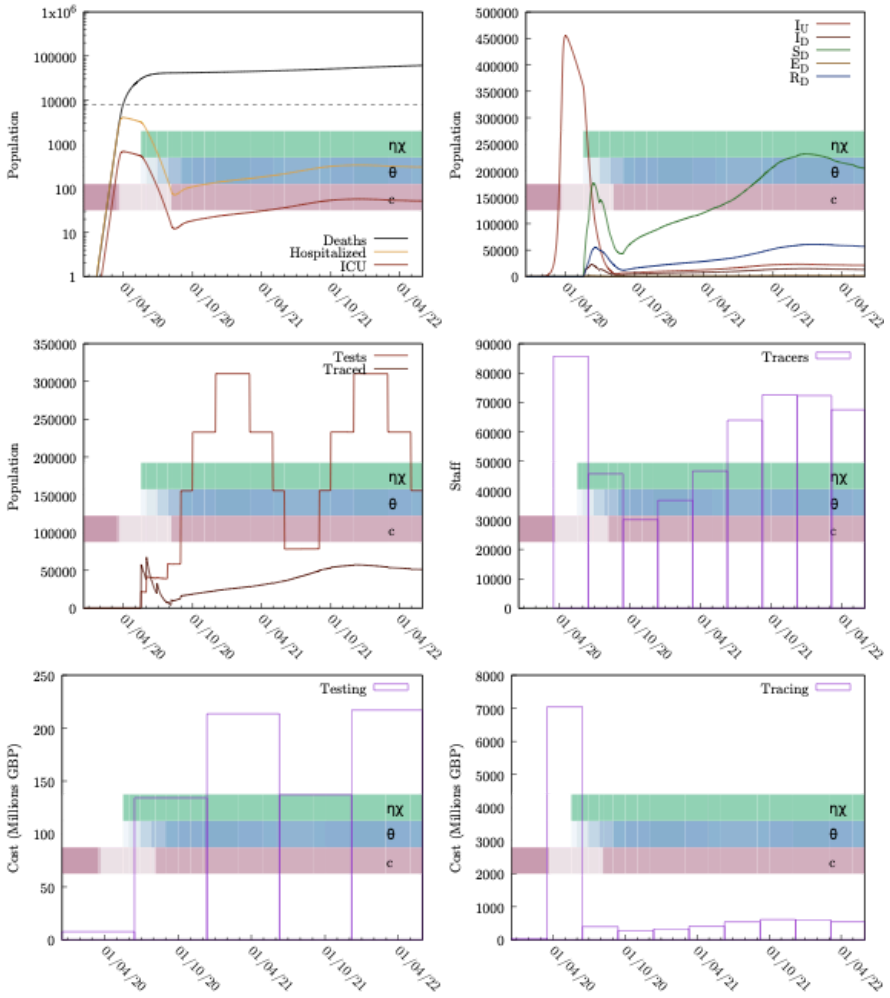


Figure S28 Scenario 4d-Trig 40% traced trajectory

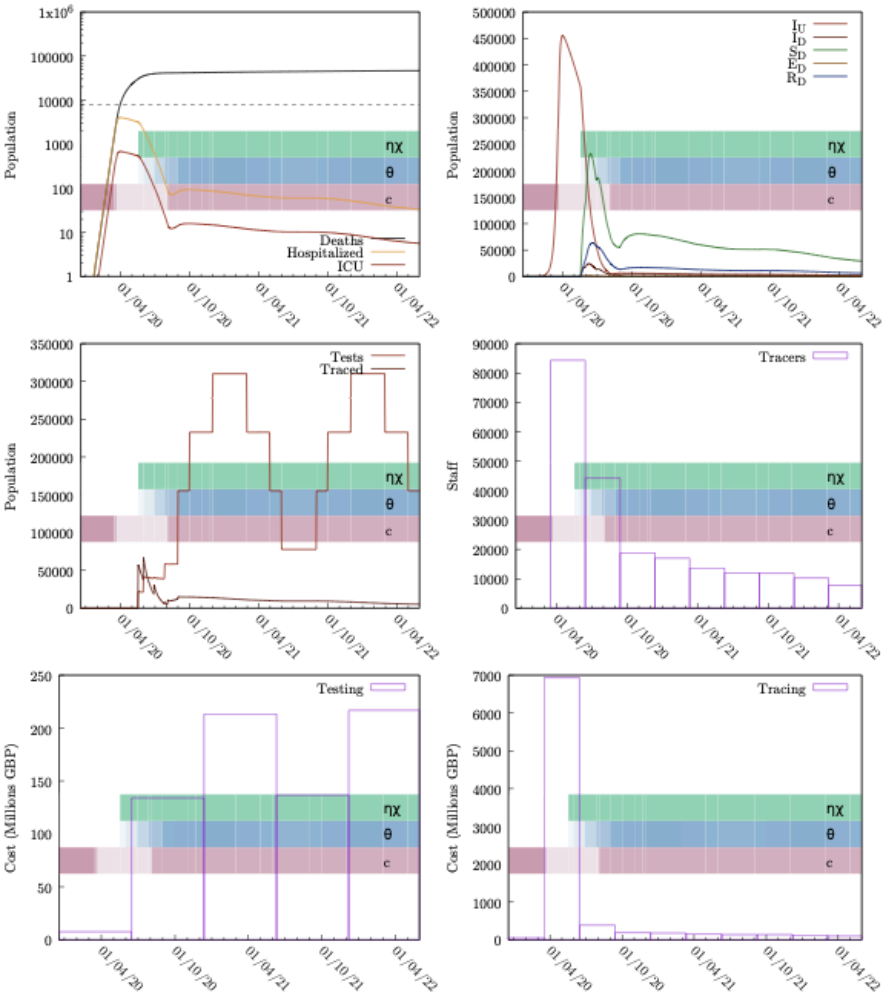


Figure S29 Scenario 4d-Trig 50% traced trajectory

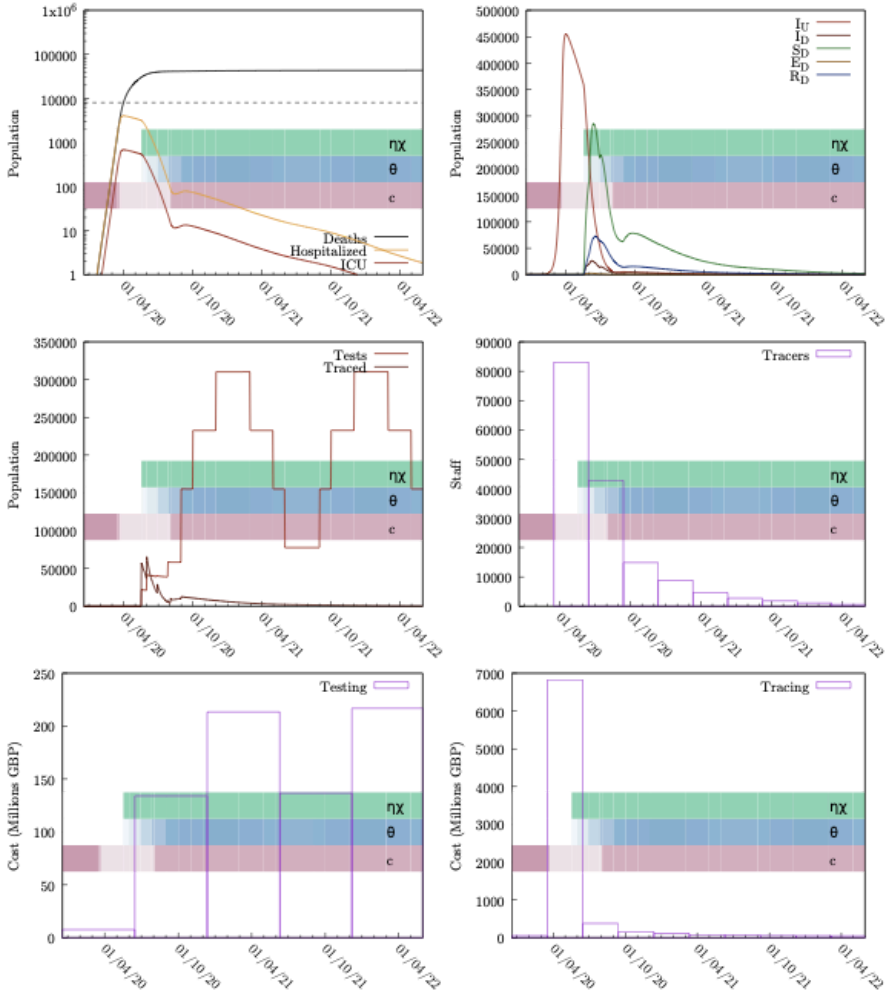


Figure S30 Scenario 4d-Trig 60% traced trajectory

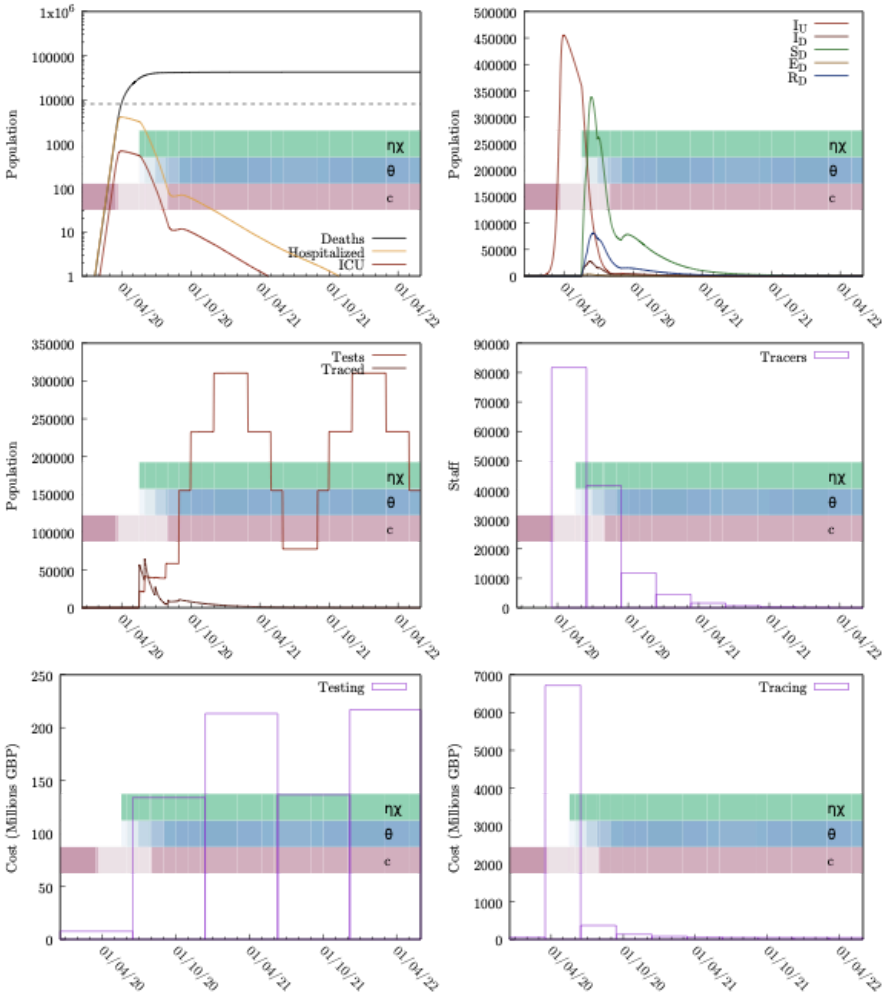
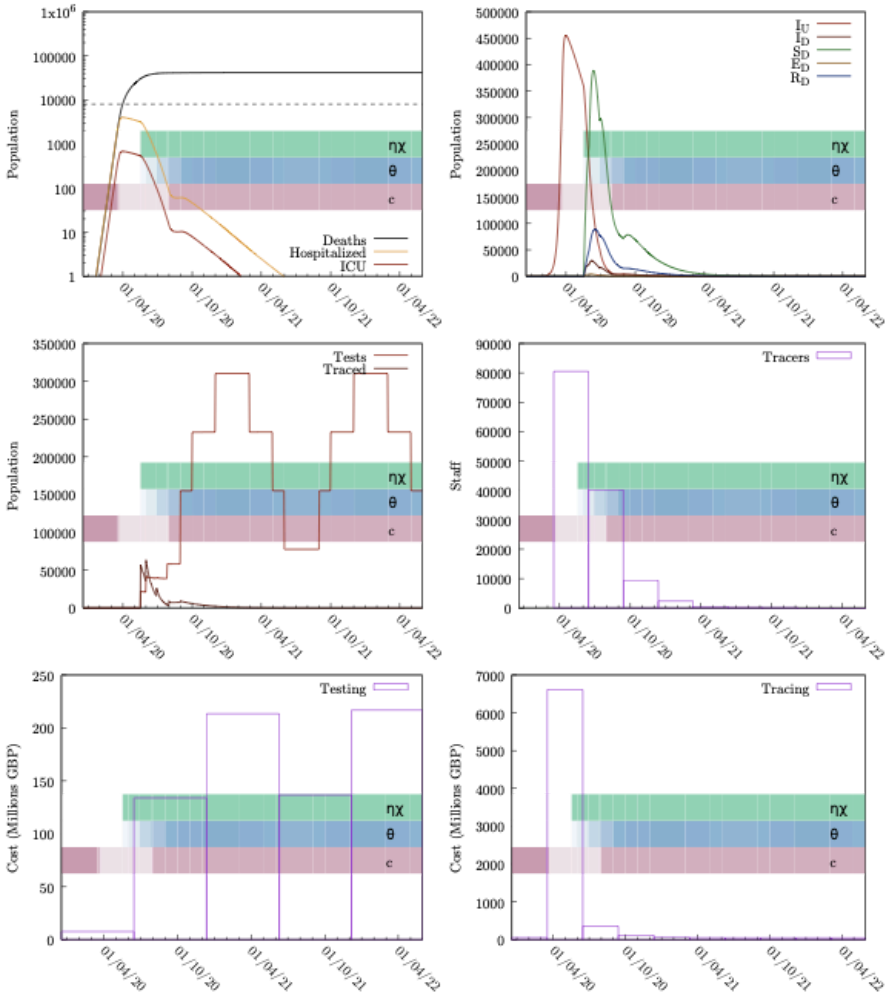


Figure S31 Scenario 4d-Trig 70% traced trajectory



Lockdown triggers

Nine scenarios have subsequent lockdowns triggered when daily new infections increase above 40,000 per day. Comparing these to the their counterpart scenarios without triggers for lockdowns (Table S7) we see that additional lockdowns were triggered when there were no interventions (scenario 1-Trig, supplementary material Figure S2), when there was initial phased lockdown release (Scenarios 2b-Trig, 3b-Trig; Figures S6, S10), and when there was targeted testing (Scenarios 4a-Trig, 4b-Trig, 4d-Trig; Figures S12, S14, S18), except for when there was a longer initial lockdown and face coverings (Scenario 4c-Trig; Figure S16).

Adding lockdown triggers benefitted scenarios without initial longer lockdowns (i.e. phased lockdown release May–July 2020, not bold font, Table S7) considerably in terms of health outcomes (~56,000–496,000 deaths averted) though with associated reduction in GDP due to additional time under lockdown (~£56bn–734bn additional reduction in GDP). Scenarios with longer initial lockdown had very similar health results (-2 to +9 deaths difference) to their counterparts with lockdown triggers (bold font, Table S7), except for scenario 4a, targeted testing, for which adding a lockdown trigger averts an estimated ~126,000 deaths. Scenarios with lockdown triggers generally resulted in additional reduction in GDP compared to the same scenario without lockdown triggers (scenarios 1-Trig, 2b-Trig, 3a-Trig, 3b-Trig, 4a-Trig, 4b-Trig, 4c-Trig, 4d-Trig, relative to counterparts scenarios 1, 2b, 3a 3b, 4a, 4b, 4c, 4d: ~£56bn – ~£734bn additional reduction in GDP; Table S7). Scenario 2a-Trig averts ~£24bn reduction in GDP compared to Scenario 2a (Table S7).

Longer initial lockdown

Scenarios with initial lockdown to 31 August 2020 to allow scale-up of testing and tracing to be completed first avert between ~57,000 and ~283,000 deaths though have ~£127bn additional reduction in GDP due to additional time under lockdown compared to their counterpart scenarios with phased lockdown release May–July 2020 (Table S8).

Face coverings

Including face coverings has a large estimated beneficial impact when untargeted testing and tracing is scaled-up to weekly testing during phased lockdown release (Scenario 3b compared to Scenario 2b, ~208,000 deaths averted, Table S9) and when targeted testing of symptomatic only is scaled-up during phased lockdown release (Scenario 4b compared to Scenario 2b, ~241,000 deaths averted, Table S9). With a longer initial lockdown whilst testing and tracing are scaled-up, face coverings avert ~14,000 deaths. Reduction in GDP is unaffected by face coverings and NHS costs are reduced in line with reduced cases, hospital cases, and ICU cases.

Untargeted large-scale testing vs. targeted testing of symptomatics

Table S10 shows that this varies a lot by initial lockdown duration, having lockdown triggers or not, in combination with face coverings or not. Under different permutations of these variables large-scale untargeted testing is sometimes better, sometimes worse, than targeted testing of symptomatics. This requires further investigation.

Table S6 PTTI results

Comparison	Scenario 2b relative to Scenario 1	With Lockdown triggers: Scenario 2b-Trig relative to Scenario-1-Trig	**With Longer initial lockdown until 31st Aug 2020: Scenario 2a relative to Scenario 1**	With face coverings: Scenario 3b relative to Scenario 1	With face coverings & Lockdown triggers: Scenario 3b-Trig relative to Scenario 1-Trig	**With face coverings & Lockdown triggers & Longer initial lockdown: Scenario 3a-Trig relative to Scenario 1-Trig**
Deaths	-251,356	-37,842	-534,232	-459,591	-51,593	-51,791
ICU cases	-58,139	-8,753	-123,569	-106,305	-11,934	-11,979
Hospital (non-ICU) cases	-329,457	-49,600	-700,227	-602,393	-67,624	-67,884
Non-hospital cases	-24,496,682	-3,688,008	-52,065,144	-44,790,779	-5,028,172	-5,047,460
NHS costs (£M)	-1,844	-278	-3,918	-3,371	-378	-380
Reduction in GDP (£M)	0	-629,964	127,543	0	-664,286	64,214
Public Health costs (£M)	734,889	36,167	36,152	177,478	31,196	31,172
of which: Testing total costs (£M)	27,807	28,251	28,252	28,016	28,258	28,260
Tracing total costs (£M)	707,082	7,916	7,901	149,462	2,938	2,912
Comparison	*With targeted testing (symptomatics only): Scenario 4b relative to scenario 1*	*With targeted testing (symptomatics only) & Lockdown triggers: Scenario 4b-Trig relative to scenario 1-Trig*	*With targeted testing (symptomatics only) & Face coverings: Scenario 4d relative to scenario 1*	*With targeted testing (symptomatics only) & Face coverings & Lockdown triggers: Scenario 4d-Trig relative to scenario 1-Trig*	***With targeted testing, face coverings & Lockdown triggers & Longer initial lockdown: Scenario 4c relative to Scenario 1***	***With targeted testing, face coverings & Lockdown triggers & Longer initial lockdown: Scenario 4c-Trig relative to Scenario 1-Trig***
Deaths	-318,280	-27,792	-492,846	-52,856	-549,892	-53,514
ICU cases	-73,619	-6,428	-113,997	-12,226	-127,192	-12,378
Hospital (non-ICU) cases	-417,175	-36,427	-645,982	-69,279	-720,752	-70,141
Non-hospital cases	-31,018,922	-2,708,540	-48,031,782	-5,151,220	-53,591,318	-5,215,343
NHS costs (£M)	-2,334	-204	-3,615	-388	-4,033	-392
Reduction in GDP (£M)	0	-523,679	0	-677,571	127,543	64,214
Public Health costs (£M)	323,526	13,011	59,401	7,995	7,918	7,918
of which: Testing total costs (£M)	714	708	709	709	700	700
Tracing total costs (£M)	322,812	12,302	58,693	7,287	7,218	7,218

Table S7 Lockdown Trigger results

Comparison	Scenario 1-Trig relative to scenario 1:	**Longer initial lockdown until 31st Aug 2020: Scenario 2a-Trig relative to scenario 2a:**	Lockdown release in May-June 2020: Scenario 2b-Trig relative to scenario 2b:	**Face coverings & Longer initial lockdown until 31st Aug 2020: Scenario 3a-Trig relative to scenario 3a**:	Face coverings & Lockdown release in May-June 2020: Scenario 3b-Trig relative to scenario 3b:
Deaths	-496,380	9	-282,866	-2	-88,383
ICU cases	-114,814	2	-65,428	0	-20,443
Hospital (non-ICU) cases	-650,614	12	-370,757	-2	-115,845
Non-hospital cases	-48,376,234	902	-27,567,560	-166	-8,613,627
NHS costs (£M)	-3,641	0	-2,075	0	-648
Reduction in GDP (£M)	733,593	-23,914	103,629	670,264	69,307
Public Health costs (£M)	0	15	-698,721	0	-146,281
of which: Testing total costs (£M)	0	0	445	0	242
Tracing total costs (£M)	0	15	-699,166	0	-146,524

Comparison	***targeted testing (symptomatics only) & Longer initial lockdown until 31st Aug 2020: Scenario 4a-Trig relative to scenario 4a:***	*targeted testing (symptomatics only) & Lockdown release in May-June 2020: Scenario 4b-Trig relative to scenario 4b:*	***targeted testing (symptomatics only) & Face coverings & Longer initial lockdown until 31st Aug 2020: Scenario 4c-Trig relative to scenario 4c:***	*targeted testing (symptomatics only) & Face coverings & Lockdown release in May-June 2020: Scenario 4d-Trig relative to scenario 4d:*
Deaths	-126,382	-205,892	-3	-56,390
ICU cases	-29,233	-47,624	-1	-13,043
Hospital (non-ICU) cases	-165,651	-269,867	-3	-73,912
Non-hospital cases	-12,316,950	-20,065,852	-259	-5,495,672
NHS costs (£M)	-927	-1,510	0	-414
Reduction in GDP (£M)	670,264	209,914	670,264	56,021
Public Health costs (£M)	-49,479	-310,515	0	-51,406
of which: Testing total costs (£M)	10	-6	0	0
Tracing total costs (£M)	-49,489	-310,510	0	-51,406

Table S8 Longer Initial Lockdown results

Comparison	Scenario 2a relative to scenario 2b	With Face- coverings: Scenario 3a relative to Scenario 3b	*With targeted testing: Scenario 4a relative to Scenario 4b*	*With targeted testing & Face coverings: Scenario 4c relative to Scenario 4d*	Longer Initial Lockdown scenarios (to 31st August 2020) relative to Lockdown release in May-June 2020 - average of all four comparisons
Deaths	-282,875	-88,579	-96,068	-57,045	-282,875
ICU cases	-65,430	-20,489	-22,221	-13,195	-65,430
Hospital (non-ICU) cases	-370,770	-116,102	-125,918	-74,770	-370,770
Non-hospital cases	-27,568,462	-8,632,748	-9,362,622	-5,559,536	-27,568,462
NHS costs (£M)	-2,075	-650	-705	-418	-2,075
Reduction in GDP (£M)	127,543	127,543	127,543	127,543	127,543
Public Health costs (£M)	-698,736	-146,305	-263,639	-51,483	-698,736
of which: Testing total costs (£M)	445	244	-14	-9	445
Tracing total costs (£M)	-699,181	-146,549	-263,625	-51,474	-699,181

Table S9 Face coverings results

Comparison	Scenario 3b relative to scenario 2b	With Longer initial lockdown until 31st Aug 2020: Scenario 3a relative to scenario 2a:	*With targeted testing: scenario 4d relative to scenario 2b*
Deaths	-208,234	-13,938	-241,490
ICU cases	-48,165	-3,224	-55,857
Hospital (non-ICU) cases	-272,936	-18,269	-316,525
Non-hospital cases	-20,294,097	-1,358,383	-23,535,100
NHS costs (£M)	-1,527	-102	-1,771
Reduction in GDP (£M)	0	0	0
Public Health costs (£M)	-557,411	-4,980	-675,487
of which: Testing total costs (£M)	209	8	-27,098
Tracing total costs (£M)	-557,620	-4,988	-648,389

Table S10 Untargeted large-scale testing vs. targeted testing of symptomatics

Comparison	Scenario 2b (untargeted large scale testing) relative to scenario 4b (targeted testing, symptomatics only)	With lockdown triggers: Scenario 2b-Trig relative to scenario 4b-Trig	**With Longer initial lockdown: Scenario 2a relative to Scenario 4a**	**With Longer initial lockdown & Lockdown triggers: Scenario 2a-Trig relative to Scenario 4a-Trig**
Deaths	66,924	-10,050	-119,883	6,508
ICU cases	15,480	-2,325	-27,729	1,505
Hospital (non-ICU) cases	87,718	-13,173	-157,133	8,530
Non-hospital cases	6,522,240	-979,468	-11,683,600	634,253
NHS costs (£M)	491	-74	-879	48
Reduction in GDP (£M)	0	-106,286	0	-694,179
Public Health costs (£M)	411,362	23,156	-23,735	25,759
of which: Testing total costs (£M)	27,093	27,543	27,552	27,541
Tracing total costs (£M)	384,269	-4,387	-51,287	-1,783
	With face coverings: Scenario 3b relative to scenario 4d	With face coverings and lockdown triggers: Scenario 3b-Trig relative to scenario 4d-Trig	**With face coverings & Longer initial lockdown: Scenario 3a relative to scenario 4c**	**With face coverings & Longer initial lockdown & Lockdown triggers: Scenario 3a-Trig relative to scenario 4c-Trig**
Deaths	33,255	1,263	1,722	1,723
ICU cases	7,692	292	398	398
Hospital (non-ICU) cases	43,588	1,655	2,257	2,258
Non-hospital cases	3,241,003	123,048	167,791	167,883
NHS costs (£M)	244	9	13	13
Reduction in GDP (£M)	0	13,286	0	0
Public Health costs (£M)	118,076	23,201	23,254	23,254
of which: Testing total costs (£M)	27,307	27,550	27,560	27,560
Tracing total costs (£M)	90,769	-4,349	-4,306	-4,306

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