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 295,000 reported cases and over 45,000 deaths as of 21st July 2020. Following the slower increase in reported cases and deaths over the last few weeks compared to earlier in the epidemic, since June the UK started to relax the physical restrictions ('lockdown') that have been imposed since 23 March 2020. This has been accompanied by a strategy to test symptomatic people for infection, trace contacts of those tested positive, and isolate both confirmed cases and their contacts. While such test-trace-isolate (TTI) policies, in combination with other measures such as face coverings, are expected to be impactful, it is important to assess which combination of strategies can both protect lives and protect the economy. This study is the first study that combines mathematical and economic

modelling to estimate the impact, costs, feasibility, and health and economic effects of different strategies.

Methods
We estimated the impact of different TTI 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 combined 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 between the start of the epidemic and May 2022. Model parameters were collated from publicly available data, and the model was calibrated to confirmed deaths associated with COVID-19 in the UK. We examined two main strategies relative to No TTI with additional lockdowns triggered if needed to suppress the epidemic: a high-coverage variant of the UK government's current TTI strategy with targeted testing of symptomatic people only; and regular population-wide TTI (PTTI) involving universal testing of a proportion of all people; both with or without the use of face coverings, and triggers for additional lockdowns. To account for uncertainty in the parameters, sensitivity analysis varied parameters for GDP loss, face covering effectiveness, proportion of infections that are symptomatic, incubation period, and infectious period.

Findings
No TTI Lockdown Triggers results in an estimated 140,000 deaths with £1.2 trillion total GDP loss. Targeted TTI Face Coverings can suppress the epidemic and results in an estimated 50,000 deaths in total and, via avoiding additional lockdown, £600bn total GDP reduction since the start of the pandemic. The Targeted TTI Face Covering strategy costs £7.1bn: £0.7bn testing costs, £6.5bn contact tracing costs. Universal PTTI is not able to suppress the epidemic further even with face coverings as we assume it will not be scaled up before contacts per day increase to a level that results in a second epidemic wave. If the infectious period is 5 days rather than 7 days or the latent period is 3 days rather than 5 days only Targeted TTI Face Coverings Lockdown Triggers is able to suppress the epidemic with an additional lockdown triggered and a consequent greater GDP reduction.

Interpretation
High coverage targeted testing of symptomatic people and tracing and isolating their contacts quickly can suppress the epidemic if accompanied by mandatory face coverings. The feasibility of TTI depends on sufficient capacity, capabilities, infrastructure, and integrated public health systems to deliver it. The political and public acceptability of alternative scenarios where subsequent lockdowns may be needed has 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.

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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 20 July 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 98 unique articles published in 2020, 23 of which have a focus on country-level COVID-19 strategy. Six of these used modelling and explored different strategies, but none combined impact studies with economic evaluation. While previous studies have modelled the impact of interventions on reduction of COVID-19 deaths and cases, most focused on evaluating the effect of physical distancing measures (lockdowns) and only look at effectiveness in terms of saving lives. Unlike previous models, our study focuses on strategies that would save lives and livelihoods, and includes combinations of contact tracing, SARS-CoV-2 viral testing, isolation of cases and contacts, and use of face coverings. 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 testing, tracing, and isolation strategy can prevent tens of thousands of COVID-19 deaths over the next two years (until 31 May 2022, when highly effective drugs or a vaccine may be available), whilst also limiting time under lockdown and associated economic damage. We establish the feasibility of PTTI, including detailing what is needed to deliver it. We have also produced a freely-available software framework for implementing this class of model with interventions (https://github.com/ptti/ptti) and a web-based app that allows users to run new scenarios in seconds: https://app.covidtti.com/.

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 locations.

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. Testing, tracing and isolation (TTI) programmes started in the UK in June, though gaps remain including coordination between contracted companies and local public health authorities, and data pertaining to the numbers of

people tested per day.[1] Coverage of testing also remains low, only picking up an estimated 40% of all infections (679 lab confirmed cases on 9th July,[2] compared to an estimate of 1700 new infections per day 6-12 July[3]). With the UK continuing to relax restrictions in July, albeit with a limited face coverings policy, it is important to assess the best way to keep infections down and prevent subsequent epidemic waves.

Recent estimates suggest that only 6.3% of the population of England (95% confidence interval [CI]: 5.0% to 7.8%) had been infected with SARS-CoV-2 as of 29 June 2020,[4] 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".[5] 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[6] 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[7,8] (or four of every six months)[7,8] until there is a vaccine to safely induce herd immunity, or highly effective drugs to prevent most deaths. Without effective provision of testing, contact tracing, and isolation (TTI), 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.[9]

Mathematical models can be used to predict COVID-19 epidemic trends and assess the effectiveness of different intervention strategies.[8,9] Existing COVID-19 models have focused on evaluating the impact of testing, tracing, and isolation (TTI) strategies to keep the epidemic suppressed.[10] Our work, instead, combines a mathematical model of the epidemic, including testing, contact tracing, isolation, face coverings, and distancing measures ("lockdown"), with an economic model to gauge the cost of the epidemic itself and the interventions intended to suppress it. Hence our work is the first to explore the impact of different interventions in terms of saving lives as well as protecting the economy–two crucial goals for the UK to achieve during the COVID-19 pandemic.[11]

We use this combined model to explore six different TTI scenarios relative to No TTI with additional lockdowns triggered if needed to suppress the epidemic and identify which strategies may allow safe reopening of the UK economy whilst protecting the public from further COVID-19 outbreaks. We examine both the effects and the costs of two main strategies: a high-coverage variant of the UK government's current TTI strategy with targeted testing of symptomatic people only; and regular population-wide TTI (PTTI) involving universal testing of a proportion of all people; both with or without the use of face coverings, and triggers for additional lockdowns.

Weekly SARS-Cov-2 testing of the population was originally proposed for the UK by Peto on 22 March 2020[12] and further detailed in a letter to the UK government on 10th April 2020.[13] Peto and colleagues have re-stated the case for regular whole population testing with saliva testing,[14] which is now being piloted with 14,000 people in Southampton.[15] Similar population-wide testing strategies have been proposed for the USA by a Harvard-led group and Paul Romer.[16,17] 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 rapid and effective home-based testing, then the epidemic can be suppressed without lockdown. With lower proportions of the population tested, such as through a targeted approach testing symptomatic people only, 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. Panel S1 (supplementary

material) considers examples from other countries where COVID-19 outbreaks have been successfully suppressed using similar strategies.

Methods

Mathematical model for transmission of SARS-CoV-2

Our model is for the whole of the UK – 67.8 million people in England, Scotland, Wales, and Northern Ireland – without any regional or demographic breakdown. We modelled the spread of COVID-19 using a novel SEIR-TTI model described in detail elsewhere.[18] 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 with unconfined and isolated subpopulations. The removed cohort includes individuals recovered from infection, hospitalised with infection, and deceased from infection with relative proportions derived from existing literature, described in the economic model section below. We used a careful probabilistic argument to account for contact tracing; we did 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.[18] 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 who 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 model parameters at a defined time. The principal parameters that are changed are the contact rate (average number of contacts per person per day) representing differing regimes of social distancing or lockdown, and the testing and tracing rates, representing building up capacity of TTI. A trigger changes parameters when a condition is met. The trigger conditions 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, which would not be politically or economically feasible. We use a threshold of <10,000 infections to release lockdown as it approximates what may be a safe level of limited community transmission. We use a threshold of >40,000 infections for beginning lockdown to reflect time elapsing between opening and closing given exponential growth.

The key model parameter that is not known from the literature is the infectiousness, β. Model calibration consisted of estimating β from the mortality data from the UK government

(https://coronavirus.data.gov.uk/) by varying β, seed date and number of infectious people at seeding as described in the supplementary material. We assumed an infection fatality rate (IFR) of 1.1% as implied by seroprevalence and death data, and a lag from infection to death of 18 days, consistent with the data from hospitalised cases in the UK and with deaths peaking around 18 days after the 23rd of March lockdown in the UK.

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

Modelled Scenarios

To account for different policy options, we examined 7 scenarios in total (Panel 1). 1. No TTI or face coverings with lockdown triggers for subsequent lockdown periods (>40,000 active infections) and lockdown releases (<10,000 active infections); 2. Universal PTTI: testing the whole population every week; 3. Universal PTTI with mandatory use of face coverings (Universal PTTI Face Coverings); 4. Universal PTTI Face Coverings Lockdown Triggers; 5–7: scenarios 2–4 replacing universal PTTI with testing of symptomatic people only (5. Targeted PTTI, 6. Targeted PTTI Face Coverings, 7. Targeted PTTI Face Coverings Lockdown Triggers). We assume scaling up to testing everyone every week (Universal PTTI) will take longer than scaling up targeted testing to cover 80% of symptomatic people (Panel 1).

Face coverings were assumed to reduce transmission by 15% in the base case, if made compulsory in public spaces. This is derived from an estimated 15–60% effectiveness outside the household (after adjusting for type of covering),[19–26] and an assumption that they would be used in 20–60% of contacts occurring in the modelled scenario trajectories[27,28]. Details are in the supplementary material.

All scenarios were run from December 2019, through lockdown beginning 23 March, until 31 May 2022. Scenarios with lockdown and release triggers diverged after 23 March when thresholds for triggers were met (<10,000 cases to release, and >40,000 cases to lock down again). Scenarios without lockdown and release triggers diverge from 20 July when different interventions are set (Panel 2; see scenario .yaml files here for full details). Lockdown release triggers were set for lockdown release to 60% of pre-pandemic contacts after lockdown release.

Panel 1: Modelled scenarios

Scenario	description	date	Cold and flu prevalence	People Tested per day[1]	$1/\theta$	% of contacts traced and isolate after days, 1, 2, 3 [2]	β	c0 =11 [3]
Base part	Baseline trajectory, common to all scenarios. 18 December 2019 chosen as seeding date in line with model fitting and new report of potential first case in France from 27 Dec, which was infected between 14 and 22 Dec. 16 March 2020: first weak measures announced to slow spread. 23 March: lockdown ordered. Phased lockdown release.	18-Dec-19	-	0	-		0.042	1
		16-Mar-20	-	0	-		0.042	0.7
		23-Mar-20	-	0	-		0.042	0.26
No TTI	**Phased lockdown release, no testing and tracing.** Lockdown lifted in a phased way as per UK government COVID-19 recovery strategy. Survey data indicates that contacts per day have only increased slightly by week of 1-8 July.	09-Jun-20	-	0	-		0.042	0.34[2][9]
		04-Jul-20	-	0	-		0.042	0.37[2][9]
		31-Jul-20	-	0	-		0.042	0.4
		31-Aug-20	-	0	-		0.042	0.45
		30-Sep-20	-	0	-		0.042	0.5
		31-Oct-20	-	0	-		0.042	0.6
Universal PTTI	**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 by end of Aug).	09-Jun-20	-	30,000	2260	47%, 72%, 85%	0.042	0.34
		04-Jul-20	-	50,000	1356	47%, 72%, 85%	0.042	0.37
		31-Jul-20	-	100,000	678	47%, 72%, 85%	0.042	0.4
		31-Aug-20	-	200,000	339	47%, 72%, 85%	0.042	0.45
		30-Sep-20	-	500,000	136	47%, 72%, 85%	0.042	0.5
		31-Oct-20	-	1,000,000	68	47%, 72%, 85%	0.042	0.6
		30-Nov-20		3,000,000	23	47%, 72%, 85%	0.042	0.7

[1] People tested in the community i.e. for purposes of tracing and isolation to control the epidemic. For Targeted testing of symptomatic people this is an approximation based on cold and flu prevalence and will vary slightly by COVID-19 prevalence, which will typically be much less than cold and flu prevalence so only make up a small fraction of those with symptoms.

[2] This is the interpretation of model parameters χ(chi) = Tracing rate per day =0.8 and (eta) = Proportion of people traced successfully and isolated ==0.8: a contact has an 80% chance of being traced and, if they are traced, they can expect it to take, on average, 1.25 days. This is modelled as an exponential distribution, $\exp(-\eta\chi t)$giving the chance of being traced at time t. The cumulative distribution, $1-\exp(-\eta\chi t)$, gives the proportion of contacts that must be traced by time t. This is 47% after the first day, 72% after the second, 85% after the third, and so forth.
We assume this is possible with a team of tracers working on each new case every day (supplemented with mobile phone apps).

[3] c = Contacts per day. c0=11 average contacts per day pre-pandemic. The numbers in this column are the proportion of pre-pandemic contacts that occur (0.26 is lockdown)

		31-Dec-20		10,000,000	7	47%, 72%, 85%	0.042	0.8
Universal PTTI Face Coverings	**Face coverings added to Universal PTTI starting 24th July when they become mandatory in shops. Reduce transmission (Beta) by 15%**	24-July-20					0.0357	
					Testing Coverage of newly symptomatic per day			
Targeted TTI, Targeted TTI Face Coverings	**Clinical case identification.** As Universal PTTI but with targeted testing of symptomatic cases identified clinically. Parameters the same as Universal PTTI and Universal PTTI Face Coverings but with targeted testing from the pool of those identified clinically (by bespoke clinical reporting system such as the one currently available to self-report symptoms and request a test[30]), as explained in the footnote.[4] Prevalence of those symptomatic with colds or flu is varied throughout the year. A proportion (rising to 80% with scale-up by 31st Aug) 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. We assume 50% of COVID-19 cases are symptomatic, though vary this from 30% to 80% in our sensitivity analysis.	09-Jun-20	1%	~20,000	20%	47%, 72%, 85%	0.042	0.34
		04-Jul-20	1%	~40,000	40%	47%, 72%, 85%	0.042	0.37
		31-Jul-20	1%	~60,000	60%	47%, 72%, 85%	0.042	0.4
		31-Aug-20	1%	~78,000	80%	47%, 72%, 85%	0.042	0.45
		30-Sep-20	2%	~155,000	80%	47%, 72%, 85%	0.042	0.5
		31-Oct-20	3%	~230,000	80%	47%, 72%, 85%	0.042	0.6
		Dec-20 – Feb-21	4%	~310,000	80%	47%, 72%, 85%	0.042	0.8
		Mar-21 – Apr-21	3%	~230,000	80%	47%, 72%, 85%	0.042	0.8
		May-21	2%	~155,000	80%	47%, 72%, 85%	0.042	0.8
		Jun-21 – Aug-21	1%	~78,000	80%	47%, 72%, 85%	0.042	0.8
		Sep-21	2%	~155,000	80%	47%, 72%, 85%	0.042	0.8
		Oct-21 – Nov-21	3%	~230,000	80%	47%, 72%, 85%	0.042	0.8
		Dec-21 – Feb-22	4%	~310,000	80%	47%, 72%, 85%	0.042	0.8
		Mar-22 – Apr-22	3%	~230,000	80%	47%, 72%, 85%	0.042	0.8
		May-22	2%	~155,000	80%	47%, 72%, 85%	0.042	0.8
No TTI Lockdown Triggers Universal PTTI Face Coverings Lockdown	**Lockdown and Lockdown Release Triggers** As No TTI, Universal PTTI Face Coverings, and Targeted PTTI Face	Lockdown release is to c = c0 * 0.6 (60% of pre-pandemic contacts) after lockdown release.						

[4] 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: if cold and flu is more prevalent than COVID-19 test results will be mostly negative. 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 of combinatorics. [31,32]

Triggers, Targeted TTI Face Coverings Lockdown Triggers	Coverings above, though instead of phased lockdown release, Lockdown released when <10,000 cases and Lockdown triggered when >40,000 cases.

Economic model

We employ a cost–consequence analysis,[33] and methods consistent with an impact inventory,[34] to evaluate our 7 scenarios. Summing across the period December 2019 to May 2022, we compare scenarios on four measures: deaths, National Health Service (NHS) costs, public health intervention costs, and reduction in GDP. Due to the complex value judgements involved we do not attempt to convert these four measures to a common metric.[34,35] Instead, we allow decision-makers to make their own assessment of the success of each scenario based on the disaggregated information (plus any additional factors they consider relevant). 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 due to 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. Public health intervention costs comprise both start-up and recurring costs for contact tracing and testing; they are blocked into three-month and six-month periods for tracing and testing respectively, based on the maximum number of infections that need tracing and testing in those periods. Details of how we derive all of these costs are provided in the supplementary material, along with potential health and social costs of lockdown that are not included in our economic model (Table S4).

Realising Resources Required for PTTI

The budget for the PTTI strategy is shown in supplementary material Table S3. 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.

Sensitivity Analysis

There is considerable uncertainty around the parameter inputs used in both the economic and epidemiological models. However, as our work is intended to inform immediate policy decisions, there is limited benefit to quantifying the cost of uncertainty and the value of future research.[36] Because all parameters can be changed arbitrarily with triggers and interventions, the total number of parameters is also very large. For both of these reasons, we did not exhaustively explore the parameter space and all possible variants of interventions and triggers or attempt to sample from such a high dimensional space probabilistically. Instead, we restricted our sensitivity analysis to deterministically varying key parameters, as described in detail in the supplement. We considered: GDP reduction during lockdown (base case 25%): 10%, 40%; face coverings' effectiveness in reducing transmission (base case 15%): 5%, 30%; and proportion of infections that are

symptomatic (base case 50%): 30%, 80%. We also varied the incubation period (base case 5 days) to 3 days to reflect a potentially shorter latent period, and the infectious period (base case 7 days) to 5 days to reflect greater infectiousness earlier in the infectious period.

Results

Table 1 shows the results of all 7 scenarios. Full results, including ICU cases, hospital cases, and non-hospital cases, are shown in supplementary Table S7, and supplementary material Tables S8–S10 compare scenario results. All scenario trajectories are plotted in six-panel figures, with Targeted TTI Face Coverings Lockdown Triggers 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 the seven scenarios; the goal is for all bars – deaths, NHS costs, reduction in GDP, and intervention (i.e. tracing and testing) costs – to be as small as possible.

Targeted TTI Face Coverings is the best option, resulting in an estimated 50,000 deaths in total and, via avoiding additional lockdown, £600bn GDP reduction since the start of the pandemic (half that of No TTI lockdown triggers). Targeted TTI Face Coverings Lockdown Triggers is similar to Targeted TTI Face Coverings because additional lockdown is not triggered. Targeted TTI is not able to suppress the epidemic without face coverings (we estimate face coverings will result in a 15% additional reduction in transmission, Panel 1, which is enough to suppress a second epidemic wave: Figure S6). Universal PTTI is not able to suppress the epidemic even with face coverings as it is not scaled up before contacts per day increase to a level (Panel 1) that results in a second epidemic wave (Figures S2–S4). No TTI Lockdown Triggers results in an estimated 140,000 deaths with £1.2 trillion GDP loss (Table 1).

The total cost of the Targeted TTI Face Covering strategy is ~£7.1bn of which £0.7bn is testing costs and £6.5bn are contact tracing costs. Universal PTTI has much higher costs, also because it is not able to control the epidemic so there are more cases requiring contact tracing.

The results of our sensitivity analyses are shown in supplementary material Tables S12-S19 and supplementary Figures S8-S15 In the base case, with a 25% reduction in GDP under lockdown, No TTI Lockdown Triggers causes a ~£600bn greater loss in GDP than Targeted PTTI Face Coverings Lockdown Triggers. With GDP reductions of 10% and 40% for time under lockdown, this difference changes to ~£200bn and ~£900bn, respectively. Varying the effectiveness of face coverings to 5% (from 15% base case) results in the Face Coverings scenarios no longer being unable to suppress the epidemic without additional lockdowns being triggered (Table S14, Figure S10). When face coverings are assumed to be 30% effective, Face Coverings scenarios suppress the epidemic more easily than when they are assumed to be 15% effective. (Table S15, Figure S11). When the proportion of infections that are symptomatic is assumed to be 30% (compared to 50% base case), targeted testing scenarios are less able to suppress the epidemic, resulting in higher mortality or more time under lockdown (Table S16, Figure S12). If the proportion of cases that are symptomatic were 80%, targeted testing would suppress the

epidemic more easily and could do so even without face coverings, with lower mortality and no additional lockdown triggered (Table S17, Figure S13). If the infectious period is 5 days (base case 7 days) only Targeted TTI Face Coverings Lockdown Triggers is able to suppress the epidemic with an additional lockdown triggered and a consequent greater GDP reduction (Table S18, Figure S14). The same is true if the incubation period (base case 5 days) is shortened to a 3 day latent period (Table S19, Figure S15).

Table 1 Scenario results

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	140,000	310,000	170,000	140,000	*230,000*	*50,000*	*50,000*
GDP reduction (£bn)	1,200	600	600	800	*600*	*600*	*600*
Public Health costs (£bn):	0.0	260	121	81	*93*	*7*	*7*
of which: Testing total costs (£bn)	0.0	25.2	25.4	25.4	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	0.0	234.9	95.6	55.3	*92.6*	*6.5*	*6.6*

Deaths are rounded to the nearest 10,000 and GDP reduction to the nearest £100bn to reflect the imprecision of the model

Figure 1: Trajectories for Targeted TTI Face Coverings. Scale-up to 80% of symptomatic people tested with 47%, 72% and 85% of contacts traced and isolated on days 1, 2, and 3 after testing by 31 August, Face Coverings policy from 24th July. 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 six-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.

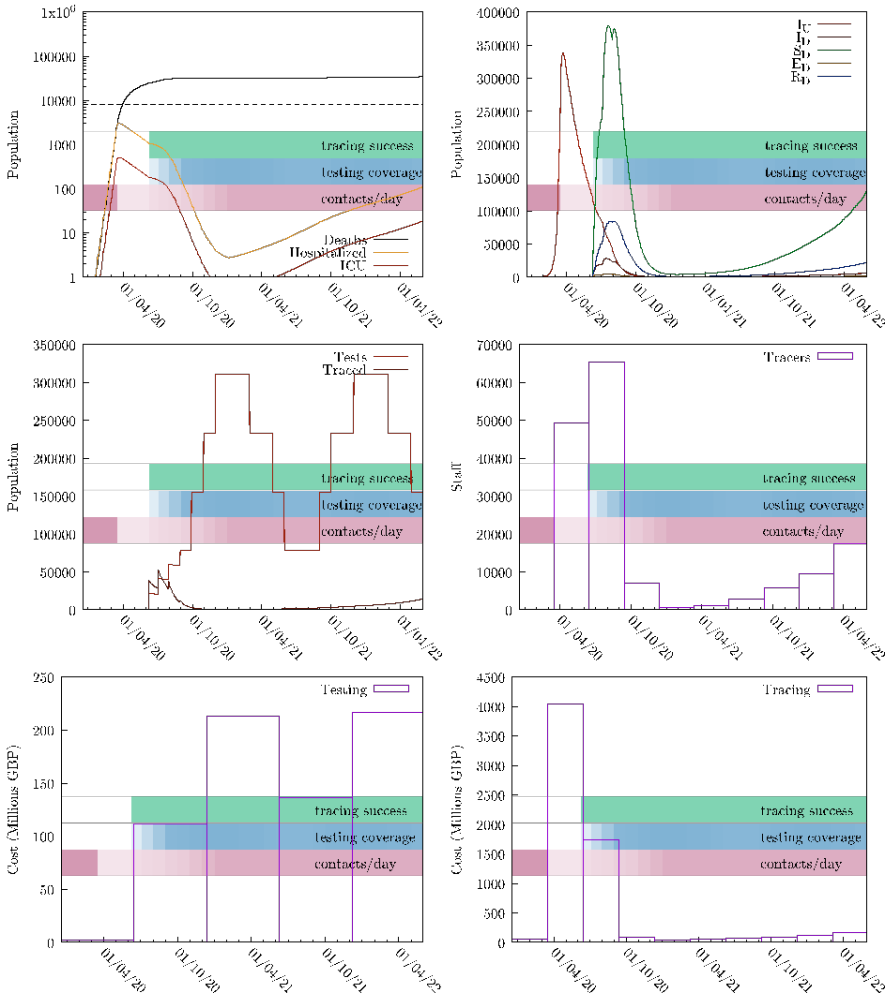
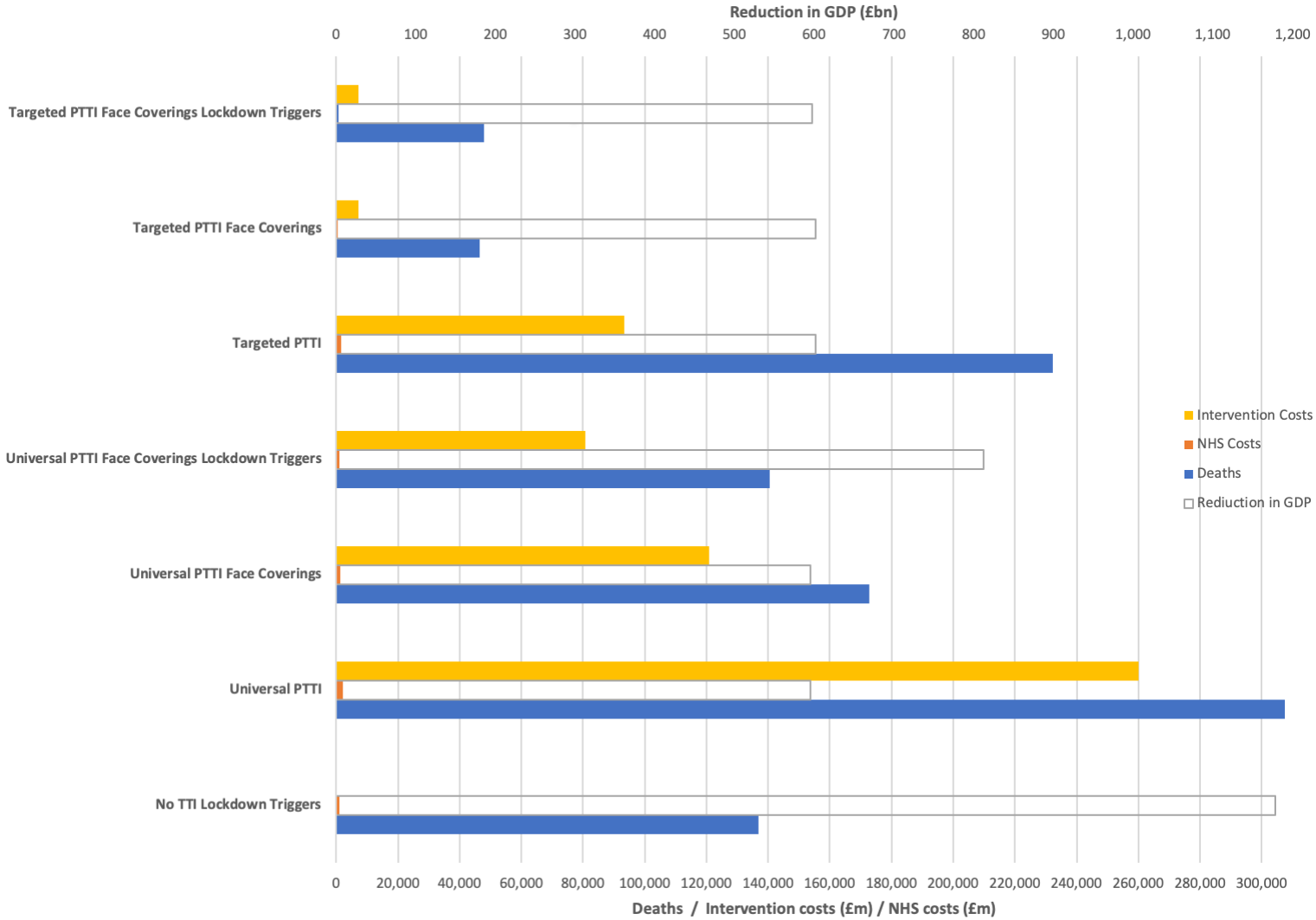


Figure 2 Health and Economic outcomes of selected Population-scale Testing, contact Tracing and Isolation (PTTI) strategies to control the COVID-19 epidemic in the UK – scenarios run to 31 May 2022.



Discussion

Our results make a strong case for expanding testing, tracing and isolation, and face coverings, immediately to control COVID-19 spread until a vaccine or highly effective drugs are available. We find that high coverage testing of symptomatic people, combined with effective tracing and isolation of their contacts, 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 before contacts per day increase sufficiently to lead to new outbreaks. We also show that population-wide use of face coverings in public spaces can make TTI strategies more effective in suppressing the epidemic, with lower cumulative deaths and less time in lockdown, in addition to lower associated costs.

Our analysis suggests the best option to protect both lives and the economy from COVID-19 is nationwide testing of symptomatic individuals and isolation of cases and their contacts, combined with mandatory face coverings in public spaces (covering ~70% of non-household contacts). This is provided contacts per day increase very gradually as this system is scaled up (Panel 1). This approach requires approximately double the number of people tested per day in the summer compared to that currently achieved for community swab "Pillar 2" tests (based on interpretation of reports as of 27 June 2020, number of people not shown[37] so hard to estimate[37]). Of the modelled scenarios, this would result in the fewest COVID-19 deaths (~50,000), the lowest intervention costs (~£7bn), and £600bn reduction in GDP by 31 May 2022, including the costs already incurred due to lockdown and the pandemic. Without TTI, we estimate that 140,000 people would die, and additional lockdowns would be required, causing around £1.2 trillion in lost GDP.

The number of tests required for targeted PTTI would rise to approximately 310,000 per day in winter when there is a higher prevalence of cold and flu symptoms, which can be confused with COVID-19. This is within the capacity of the 500,000 tests per day by the end of October promised by the UK Prime Minister on 17th July 2020. 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 47% of contacts are traced by the end of the first day after the test, 72% by the second, 85% by the third, and 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, and is consistent with a recent study simulating tracing in Boston which concluded it could be successful in suppressing the epidemic with 40% of contacts of 50% of symptomatic cases traced.[38] While universal testing can also detect asymptomatic and pre-symptomatic infections, it would need four million people tested each day to pick up the same proportion (40%) of infections, and is therefore less efficient than targeted testing with tracing and isolation of contacts.

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,[39,38,40–42 43] includes an 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.[11] We 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[39] or isolates a proportion of exposed individuals[38,40–42] does not adequately capture the dynamics of contact tracing.[18] An alternative is detailed individual-based models (IBMs) tracking the transmission of individuals,[43] and existing detailed IBMs come to broadly similar conclusions.[10] 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[10] 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.[44]

Finally, our approach generates actionable policy insights.[45] Some recent analyses of policies do not model contact tracing as an option,[46–48] leading to conclusions about trade-offs between a non-exhaustive set of options. It is important to note that PTTI could be abandoned when drugs or a vaccine become available without irrecoverable ("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 three-month contracts) or six months (e.g. laboratories, lab worker contracts; Table S3).

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. To explore this possibility in our deterministic sensitivity analysis we changed the infectious period from 7 days to 5 days to simulate earlier infectiousness and found only Targeted TTI Face Coverings Lockdown Triggers was able to suppress the epidemic with an additional lockdown triggered and a consequent greater GDP reduction (Table S14, Figure S18).

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 S4. Given Public Health England's recent report outlining the variability of impact of COVID-19 between ethnicities, socioeconomic status, and occupation,[49] this is an important caveat. 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 PTTI 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. This work should involve encouraging uptake of testing in geographical hotspots and for high-risk groups such as key workers and BAME people.

The exact numbers of deaths averted depend on assumptions about the proportion of the country that has already been infected, and relatedly, the infection fatality rate. These parameters remain uncertain though we use what we believe are the best currently available estimates.[5,7,50] 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, or costs to provide separate accommodation for people to isolate in, though unlike other studies, we do not assume perfection.[52] Policies to support effective isolation, such as community support and volunteers to run errands for those isolated are important. Costs of enforcement may be covered by a combination of using existing policing systems and paying for additional measures with fines gathered from violators.

This is a well-mixed model, meaning that each non-isolated individual has an equal chance of encountering any other non-isolated individual. This structural assumption tends to overestimate the spread of the disease. Real populations have more structure, meaning the pool of susceptible individuals in a local contact network can become exhausted and retard propagation of the virus through the population. 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 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.

We do not include parameters for test sensitivity and specificity in our model, though we note that the effects of the test being less than perfect can be estimated. For example, if the test is 80% sensitive then the testing coverage would need to be increased by 1/0.8 to have the same effect. If the test is 95% specific then 5% of those traced and isolated will have been unnecessarily isolated. We note that reports to date suggest that RT-LAMP tests for SARS-CoV-2 have sensitivity and specificity similar to RT-qPCR[53], and that self- collected saliva samples compare favourably with nasopharyngeal or oropharyngeal swabs[54]).

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. 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 actual impact on the UK economy is far from understood, and the degree of shutdown is only a rough proxy for economic impacts. Many alternative proxies that would be compatible with the epidemiological model are no better at representing loss, and are far less transparent.

The costs of testing are converging around our estimate given new methodologies that can be applied at scale.[15] Importantly, our conclusions regarding the need for targeted TTI to suppress the COVID-19 epidemic in the UK instead of lockdown would remain 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 or cost-effectiveness analysis, which would require a number of highly subjective judgements. In addition, 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.[1] 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, population mental health, and non-COVID-19 disease.

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, and DF 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.

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Data sharing

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

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Supplementary Material

Panel S1: Evidence of successful implementation of population-scale testing, tracing, and isolation strategies

Here, we summarise six case studies demonstrating successful approaches to suppressing COVID-19 outbreaks at the city or country level. Whilst all involve widespread use of testing, tracing, and isolation, they highlight different elements of PTTI strategy: large-scale clinical screening (Wuhan), contact tracing (South Korea, Vietnam, Taiwan), and testing (Vo). Other aspects of the national COVID-19 response, such as physical distancing measures and mask usage, also contributed to success in controlling the epidemics in these places.

Wuhan, China - Wuhan, the epicentre of the global outbreak, trialled a number of control approaches. The city was quarantined on 23 January 2020, with restrictions relaxed on 8 April.[55] Testing capacity and accuracy was limited at first, so clinical case identification was heavily relied upon, with nearly 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[56] and suppressing the epidemic to negligible levels within a month. Following another small outbreak, Wuhan again tested most residents between 14 and 24 May. This identified zero symptomatic cases, and only 300 non-symptomatic infected cases, all of which were isolated.[55]

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.[57] All traced contacts are tested, and positive cases are isolated. 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.[58]

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 face masks from 16 March.[59] Contact tracing, testing, and isolation has been key to containment, with a four-level system in place:[60] (1) confirmed cases and their direct contacts (isolation/hospital treatment); (2) close contacts with level 1 (quarantine in dedicated facilities); (3) close contacts with level 2 (self-quarantine at home); and (4) lockdown of the area where the patient lives. Extensive testing – using home-grown testing capacity[61] – 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.[57] As of 7^{t} June, there have been 329 documented COVID-19 cases in Vietnam, with only 67 cases recorded in the preceding eight weeks,[62] and zero recorded COVID-19 deaths.[62]

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 in 2003, the Taiwanese CDC exercised its broad powers and was quick to implement control measures: over 100 measures were already set in place before March,[63] 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[63]), 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.[63]

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).[64] Contact tracing and transmission chain reconstruction were used to determine that the majority of transmission during lockdown resulted from asymptomatic household members.[64] This was minimised with the quarantining of those testing positive, and the epidemic was halted in 14 days.[65]

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.[66,67] Although it did implement a 21-day lockdown, its success has been partly attributed to its rapid mobilisation of a local test, trace, and isolate programme. This combined strict adherence to WHO guidelines with local innovation, including a real-time COVID-19 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.[68]

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.[18]

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 0.4, 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 0.64

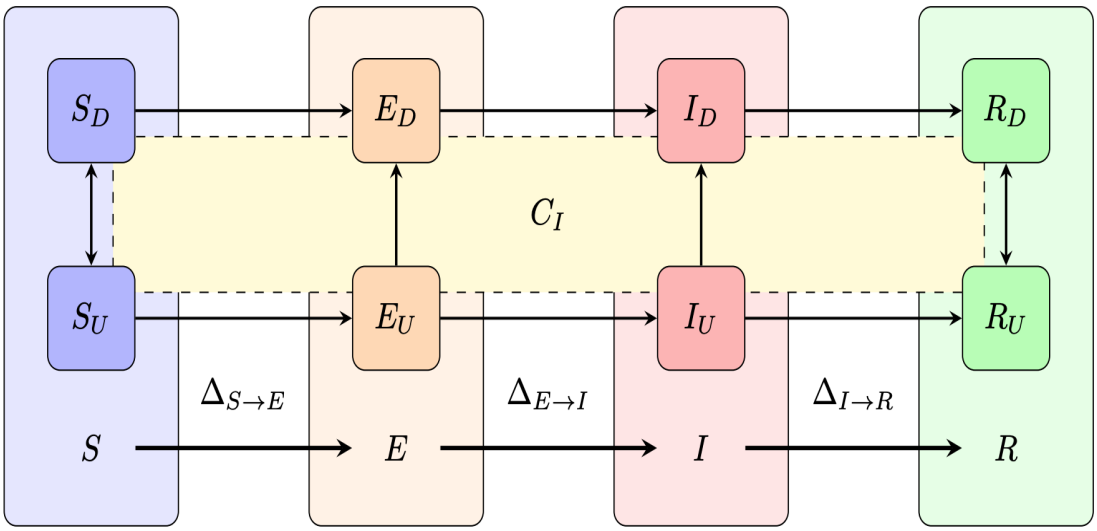


Figure S1 Schematic of an SEIR model with diagnosis described by testing and contact-tracing. SEIR is a compartmentalised model describing susceptible (S), exposed (E – infected but not infectious), infectious (I) and removed (R) population cohorts. Individuals move between these compartments in sequence 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 $\Delta X \to Y$ 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[18] 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 days and the infectiousness period of COVID-19 of 7 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,[69] which aligns with earlier UK data on social contacts.[70] 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 74% reduction in *c* from lockdown on 23rd March 2020,[71] which we assume applies for the duration of the lockdown. For the relaxation of lockdown we use estimates of *c* increasing to 35% of baseline from 9th June (week of 5th-12th June 2020,[29]) and 37% of baseline by 4th July (despite pubs opening, week of 1-8th July[29]) then assume *c* continues to increase slowly to 40%, 45%, 50% and 60% of baseline by the end of July, August, September and October respectively, and finally to 80% of baseline by the end of December 2020 providing no additional lockdowns have occurred (Panel 1). We assume no further increases in contacts per day throughout the next two years to 31st May 2022 (the end date of our scenarios) given likely semi-permanent changes to pre-pandemic contact patterns due to a general wariness of the population due to the pandemic.

We assumed an infection fatality rate (IFR) of 1.1%, based on a recent seroprevalence survey suggesting IFR may be around 1.1%: an estimated 5.4% of the UK population (95% CI: 4.3% to 6.5%) – around 3.7 million individuals – had antibodies to SARS-Cov-2 as of 13 June 2020,[472] while deaths were estimated at 41,000,[73] implying an IFR of 1.1% (0.9%, 1.4%). Deaths may have been as high as 60,000,[74–76] which would indicate an IFR of 1.6% (1.3%, 2.0%).

We assumed a lag from infection to death of 18 days. This is consistent with deaths peaking in the UK on 10 April [77], 18 days after lockdown on 23 March. Moreover, data from thousands of hospitalised cases in the UK shows a median duration of symptoms before hospitalisation of four days and a median duration of hospitalisation of those who died of about eight to nine days[78] (Figure E4 in the data supplement of the paper[78]). Adding the five-day incubation period (Table S1) and pre-symptomatic infection period of 0.5–1 day, these figures suggest a lag to death of around 18 days.

Table S1 Model parameters

Parameter	Description	Default Value*	Reference
N	Population size (UK population mid-year 2020)	67,886,011	[79]
c	Average contacts per day	11	[69]
β (beta)	Transmission rate per contact	0.0435	Estimated from fit to mortality data[73]
α^{-1} (alpha)	Incubation period (time from exposed to infectious)	5 days†	[80–83]
γ^{-1} (gamma)	Recovery period (time from infection to recovery or hospitalisation)	7 days†	[84,85]
κ^{-1} (kappa)	Isolation period (symptom free days)	14 days	[86]
θ (theta)	Testing rate of infectious individuals	0	-
χ (chi)	Contact tracing rate	0	-
η (eta)	Efficiency or success rate of contact tracing and isolation	0	-

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

We assume face coverings reduce transmission by 15% in the base case, with 5% and 30% used in the sensitivity analysis. These figures are obtained by multiplying the effectiveness of face coverings by the proportion of contacts in which they will be worn.

The evidence does not currently allow a precise estimate of the effect of face coverings on community transmission of SARS-CoV-2. Although a large randomised controlled trial (RCT) is currently underway in Denmark, the only two completed clinical studies of masks in COVID-19 are observational: in a non-peer-reviewed pre-print, Doung-ngern and colleagues[32] report a large protective effect of wearing a mask "all the time" (adjusted odds ratio [OR] 0.23 [95% CI 0.09–0.60]), but not "sometimes", among contacts of cases in Thailand; and Wang and colleagues[87] find similar benefit (OR 0.21 [0.06–0.79]) in China within households. However, two recent systematic reviews with meta-analyses have examined mask usage in related viruses. Chu and colleagues[30] report a 44% reduced risk (risk ratio [RR] 0.56 [95% CI 0.40–0.79]) for non-healthcare settings (including households), based on three case control studies during the 2003 SARS-CoV-1 pandemic. Similarly, in an analysis that included studies of influenza as well as SARS-CoV-1, Liang and colleagues[31] find an OR of 0.44 (0.33–0.59; n=5 studies) among non-healthcare workers (HCWs) outside of the household, with greater benefits among HCWs and within households. Overall, these studies suggest universal mask-wearing would reduce the risk of infection by 20–80%, with a best guess around 50%.

Importantly, these studies only examined the effect of mask usage among the susceptible population, i.e. for protecting the *wearer*. We could not find direct evidence on masks for community-based "source control", i.e. worn by infectious individuals, for COVID-19 or

other coronaviruses. Nevertheless, there are several reasons to believe effect sizes based entirely on the protection of well individuals understate the benefits of compulsory face coverings.[23–25] First, a small number of clinical studies of face coverings for source control in influenza have found a benefit to household members (though results overall are mixed[23,88]). Second, masks have been shown to reduce emission of various pathogens, including influenza viruses and Mycobacterium tuberculosis, in experimental conditions.[89,90] Third, there is some evidence that SARS-CoV-2 is more reliant than other pathogens on relatively large droplets for transmission,[91–93] and masks are better able to filter out droplets than small particles. This may help explain the larger protective effect[31] in SARS-CoV-1 (a virus closely related to SARS-CoV-2) compared to influenza. Fourth, it has been established that transmission from asymptomatic individuals is common in SARS-CoV-2,[94–96] which shows we cannot rely on infected individuals taking measures to reduce spread once they become sick. Fifth, anecdotal evidence suggests "superspreading" events are much more likely to be caused by individuals who do not wear a mask.[23,97] While the size of the additional benefit is very unclear, we believe this evidence warrants an increase in the estimated effect size of universal mask usage to around 65% (35–90%).

On the other hand, the face coverings used in relevant studies are typically medical masks, or made of unspecified material. A recent survey[98] found just 30% of face coverings currently used by the UK public for protection against SARS-CoV-2 are medical, the rest being home-made cloth masks (26%), shop-bought cloth masks (23%), and improvised coverings such as scarves (17%). The UK government itself provides instructions for making a mask out of a single layer of T-shirt material.[22] The only RCT comparing mask types found that three-layer cloth masks were about half as effective as surgical masks in preventing laboratory-confirmed viral infection (mostly influenza) among hospital staff, and about 13 times less effective at preventing flu-like symptoms[99] – although the difference is likely to be smaller for coronaviruses.[24] When including studies in a healthcare setting, Chu et al.'s review[19] finds some evidence of effect modification by mask type, with descending (though overlapping) effect sizes for N95 respirators (adjusted OR 0.04 [0.004-0.30]), surgical masks (0.20 [0.06-0.63]), 12–16 layer cotton masks (0.33 [0.10–1.03]), and single-layer masks (effect size not reported). In its own meta-analysis[26] of data from Chu et al.,[19] Liang et al.,[20] and Wang et al.,[87] the Institute for Health Metrics and Evaluation (IHME) likewise found smaller effects with “paper/cloth or nondescript” masks, both when used in healthcare (medical masks: RR 0.42 [0.34–0.53]; other masks: 0.51 [0.38–0.66]) and in the general population (medical: RR 0.55 [0.42–0.72]; other: 0.67 [0.49–0.88]). Experimental evidence and common-sense reasoning further support the conclusion that effectiveness will depend on material type and density, number of layers, closeness of fit, frequency of washing, and other factors that are likely to vary widely among face coverings used by the general public.[24,94,100–106] In the absence of precise figures, we make a subjective 50% (25–75%) downwards adjustment to our previous estimate, yielding a protective effect of about 33% (10–60%) for universal mask-wearing.

The proportion of contacts in which a face covering would be used by at least one party is equally difficult to estimate. In the UK, where masks have been compulsory on public transport since 15 June, self-reported mask usage had reached just 38% by 12 July.[27] However, the same survey suggests over 80% compliance in countries with such laws in place, Transport for London claims over 90% usage on trains and buses,[28] and polls have found high levels of public support for making masks mandatory in shops on 24 July[107] and belief in their effectiveness.[108] Based on this weak evidence, we tentatively assume 70% of contacts outside the house will involve at least one mask under such a policy. As

shown in Table S2 below, if we further assume two non-masked contacts per day are within the household, with total contacts ranging from three to nine across our simulated period, around 20–60% of contacts will be protected by a mask. Multiplying this by our effect size, we obtain a very rough estimate of 15% (5–30%) reduction in overall transmission (β). While not directly comparable, this is broadly consistent with the substantial benefits from compulsory masking that have been found at a city, state, and national level during the COVID-19 pandemic.[109–115]

Table S2: Mask protection with differing numbers of daily contacts

Contacts per day	Household contacts per day	Non-household contacts per day	% of non-household contacts protected with a mask	% of all contacts protected with a mask
3	2	1	70%	23%
4	2	2	70%	35%
6	2	4	70%	47%
8	2	6	70%	53%
9	2	7	70%	54%

Model calibration

Calibration of the model projections to available data is described in detail and visually shown in the documentation for our software.[5] 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 1.1% 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 0.0435 (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 around 0.9 and the data from before that time is of poor quality.

Furthermore, it must be emphasised that this onset date is notional, for the purposes of the model. The purpose of this work is to explore possible future scenarios, not to make claims about the origins of the epidemic in the UK. It could easily have been the case that the virus was imported into the country multiple times by multiple individuals later than this notional seed date. This date is merely the technical answer to the question, "if the epidemic began with a single individual, and

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

if it were appropriate to model the early stages of the epidemic with a system of ordinary differential equations, at what time would we have had exactly one infectious individual such that the model produces the correct number of deaths from March onwards?" This is not a valid procedure for investigating the origins of the epidemic. This is a valid procedure for anchoring the model for exploring the future and should be understood as that and nothing more.

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.

In our sensitivity analysis we vary the proportion of infected individuals who are symptomatic from our base case assumption of 50% to a low estimate of 30% and a high estimate of 80%. A recent review identifies studies estimating the true proportion could be between 43% and 98% (asymptomatic proportion: 2% to 57%[116]). Because the relative effectiveness of targeted testing compared to untargeted testing depends on this parameter our sensitivity analysis is intended to be conservative i.e. the low estimate of 30% may be lower than the true proportion symptomatic. The closer the high estimate is to 100% the similar the results of targeted testing will be to untargeted testing given much of the effect is driven by tracing and isolation of contacts preventing chains of transmission.

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-19 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[117] – 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[78] and 36.3% of non-ICU hospitalised cases die due to COVID-19.[78] 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,[118,119] factoring a mean of three organs supported;[120] and £346 per day for non-ICU cases.[121] 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.[78] 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,[122] 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. the country is not back to $c = 11$ (100%) normal economic activity.

Intervention costs

Intervention costs are calculated by dividing the budget items shown in Table S3 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 seven 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 three-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 S5). 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[123] 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 S3: 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	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	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-19 supervisor	Supervisor / manager for PHCOs - ~1 per 50, or ~4 per each of the 343 local authority areas	1629	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	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	£200 per recruitment for advertisements, phone interviews, salary of recruiters	£200	

Equipment	Function	Number	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	all staff above	£5	
				Unit cost	
Smart phones	only for ~10% of staff who don't have one	8,350	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	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	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	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	Rationale for number	Salary per day	Notes
Lab technicians	running SARS-Cov-2 viral RNA RT LAMP tests	11,574	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	two one for each lab (one for each 9hr shift) - average 10 RT LAMP machines per lab	£300	
Lab staff training	training on running RT LAMP tests	12,153	Initial 2 day training, 1 day refresher every 3 months	£200	5 days training per year
				unit cost	
Recruitment costs	Recruitment costs for all lab staff, including for replacements and cover	12153	£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	Estimated cost of £500 per day per lab for 289 labs with 10 RT LAMP machines in each	£500	

Machines				**RT LAMP machine cost per day**	
START-UP COSTS: RT LAMP Machines	SARS-Cov-2 viral RNA RT LAMP testing. Also automatically uploads data to online health records	2,894	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 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 Machine maintenance	maintain working order of the 2894 RT LAMP machines used	2,894	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	10 million tests per day	£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	10 million tests per day[12]	£0.50	Home collection by couriers - used for costing for 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

* costs of testing are based on a pilot study in Southampton of mass home-based saliva testing that has now been approved and started.[15]

Cost of face coverings

We assume that if people are unable to afford their own face coverings they will be wearing reusable face coverings made from materials to hand in the home, at little or no cost. The UK government has already issued advice on how to make and properly use a face covering: https://www.gov.uk/government/publications/how-to-wear-and-make-a-cloth-face-covering/how-to-wear-and-make-a-cloth-face-covering.

Additional health and social costs of lockdown

Table S4 shows potential health and social costs of lockdown that are not included in our economic model.

Table S4 Potential Health and Social Impacts of COVID-19 lockdown and impact on NHS of COVID-19 demand[124]

Sector			Processes affected	Potential adverse health outcome
NHS	Programmes	Screening across the lifecourse, e.g. neonatal, cancer	Delivery, uptake and action[125]	Avoidable morbidity and mortality
		Immunisation	Reduced uptake[126]	Reduced herd immunity Increase in vaccine preventable infection
	Child and adolescent health		Health visitor checks and support for parents Adolescent mental health[127] 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[128]	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[129]
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[130] Disrupted support services during lockdown Removal of temporary housing at the end of COVID-19	Poorer health outcomes
	Dementia	Isolation, less carer support[131] Harms e.g. falls	Poorer quality of life Higher morbidity and mortality
	Patients with disability	Access to services for complex medical needs[132] Isolation Anxiety – may not be a ‘priority’ group for ICU	Worse health outcomes

		Inequity in access to public health messaging	
	Severe mental illness (inpatient services)	Deterioration, potential 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 Higher COVID-19 risk due to poor living conditions[133] 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: in the UK NHS Charging Regulations deter migrants from accessing health services (particularly those undocumented) Culturally or linguistically inappropriate care Increased discrimination/xenophobia during COVID-19[134] 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	Poorer health outcomes Higher COVID-19 mortality for BAME groups[135] 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[136] Increased rates of depression[136] Increased rates of condition related anxiety (COVID patients)[136]	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)	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)

			Lack of access to free school meals for children who need them, and increased use of food banks	
	Access to food	Especially 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[134]				

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.[137] Nevertheless, personal follow-up on foot will also be required to ensure all contacts, including the most vulnerable, are reached.[138] 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.[139,140] 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.[141]

Case finding and contact tracing
Contact tracing remains a key control measure for maintaining suppression of case counts.[142] Table S5 shows the staff needed to handle new cases and control spread through contact tracing and isolation.[143] Table S6 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 S6. It seems that the service is limited to phone and internet communication with individuals. Because the levels of ascertainment of cases of this approach remains unknown, it will be prudent for local authorities to assume that at least half the manpower shown in Table S6 will be required by them.

Table S5 – 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[144] and R_0 of 2.5[145])	

***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.[146]
†**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.[146]

Table S6 – 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 the No TTI scenario	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 the No TTI scenario	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 the No TTI scenario	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)				1,759,526										2,089,994
30th April	194,720	45,991	89,757		117,945	272,608	200,654	140,198	191,011	178,030	175,804	259,997	132,410	
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: TheONS 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 the No TTI scenario.

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[143] (these numbers in Table S6 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[147] are used by sufficient numbers of individuals here and their accuracy increases (though we do not assume any increase in efficiency or success of contact tracing resulting from use of phone apps). On average there will need to be 5.1 full time trained contact tracers (Public Health Community Officers, PHCO; Table S3) to cope with each additional concurrent case, though this will vary by the number of contacts per day. 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, as 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.[148] Most local authorities have established volunteer registers[149] 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 S6).

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.[150] 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,[151,152] which has been affirmed by evidence from previous epidemics including HIV[153,154] and Ebola.[155] Community-led and co-production approaches in the context of the COVID-19 response have been lacking,[156] 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 implementers 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-19 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.[157] 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[158,159] and can have positive knock on effects for mental health outcomes in the general population, which is a growing concern in the crisis.[160]

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 three 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.

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[13] 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”[161] can be dealt with using the strategy developed by the ONS.

2. New 96-well machines running direct RT LAMP assays[162] 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, LAMPreagents (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. LAMP 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 isolation following a positive test. Isolation 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 isolation 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 households in isolation with access to income compensation, mental health support and food delivery.

These pilot studies, one of which has started on a smaller scale in Southampton with 14,000 people,[15] 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 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 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

PTTI 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.[16,17] The UK government's five-pillar plan for scaling up COVID-19 testing[163] reaches out to local manufacturers to ramp up testing capability and pharmaceutical companies are also offering to help.[164] 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 three 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.[165] 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[166] (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.[167] 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.[167]

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[168]).

Supplementary Results - Scenario trajectories

Figure S1 No TTI Lockdown Triggers trajectory

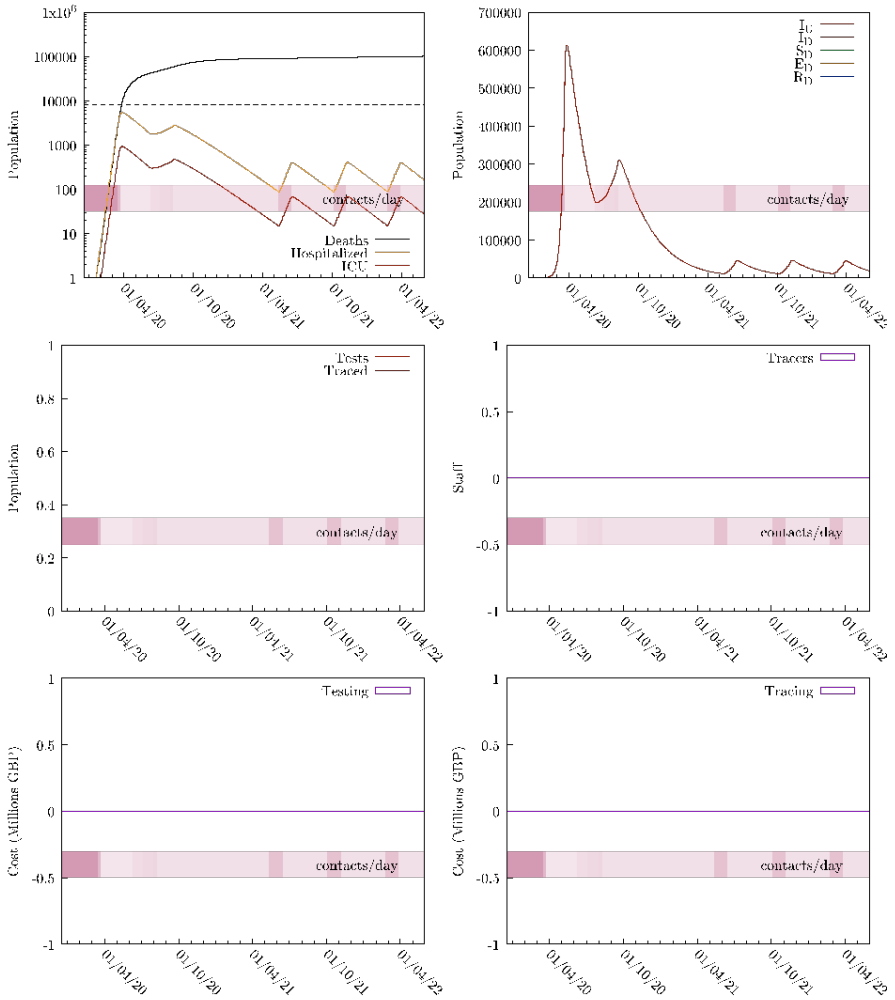


Figure S2 Universal PTTI trajectory

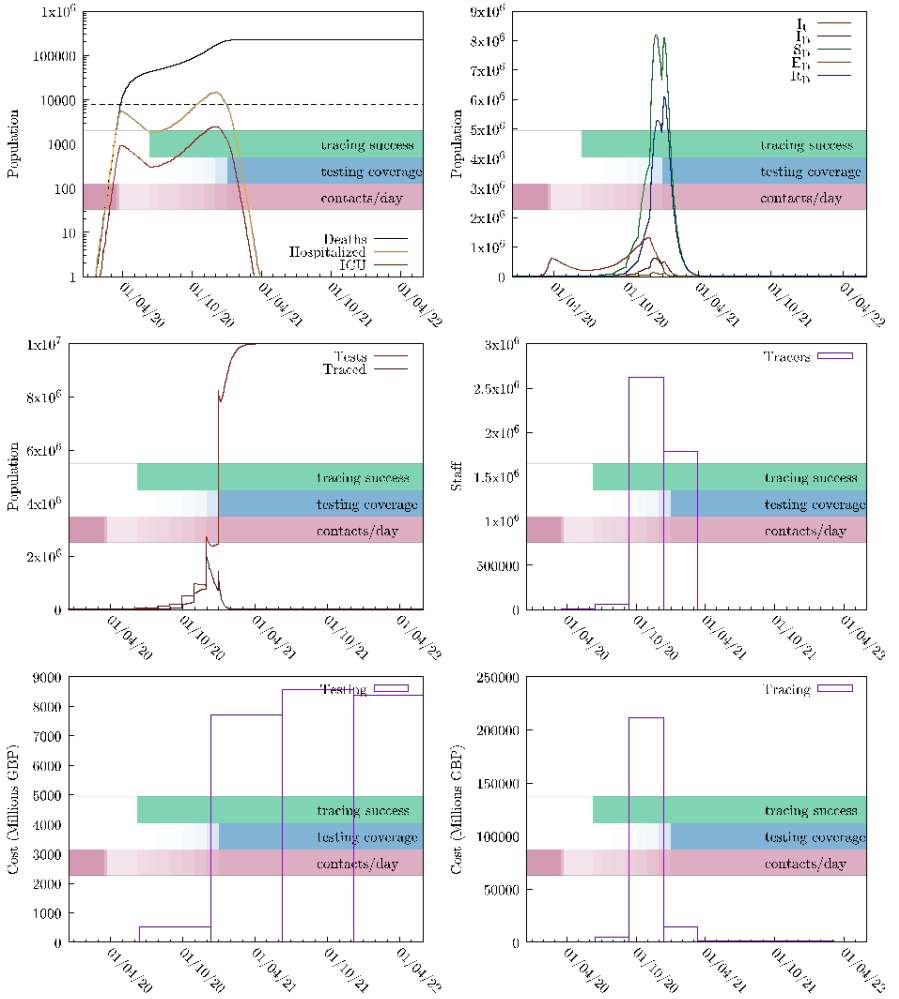


Figure S3 Universal PTTI Face Coverings trajectory

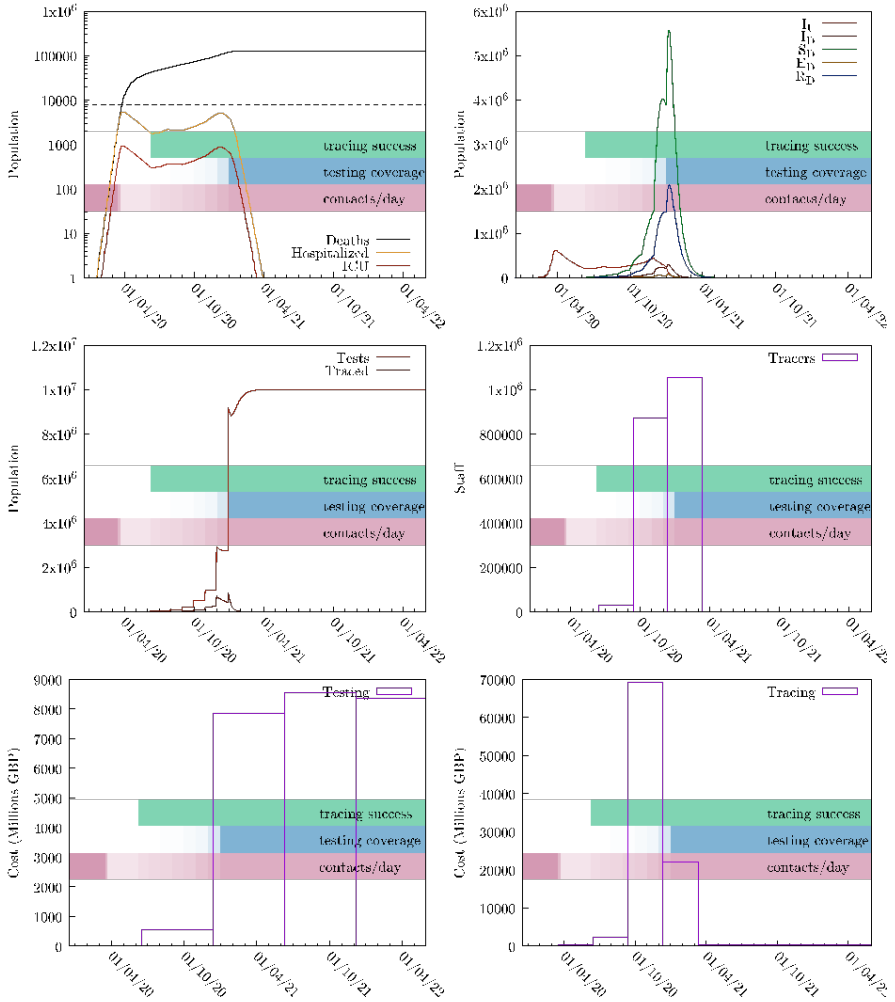


Figure S4 Universal PTTI Face Coverings Lockdown Triggers trajectory

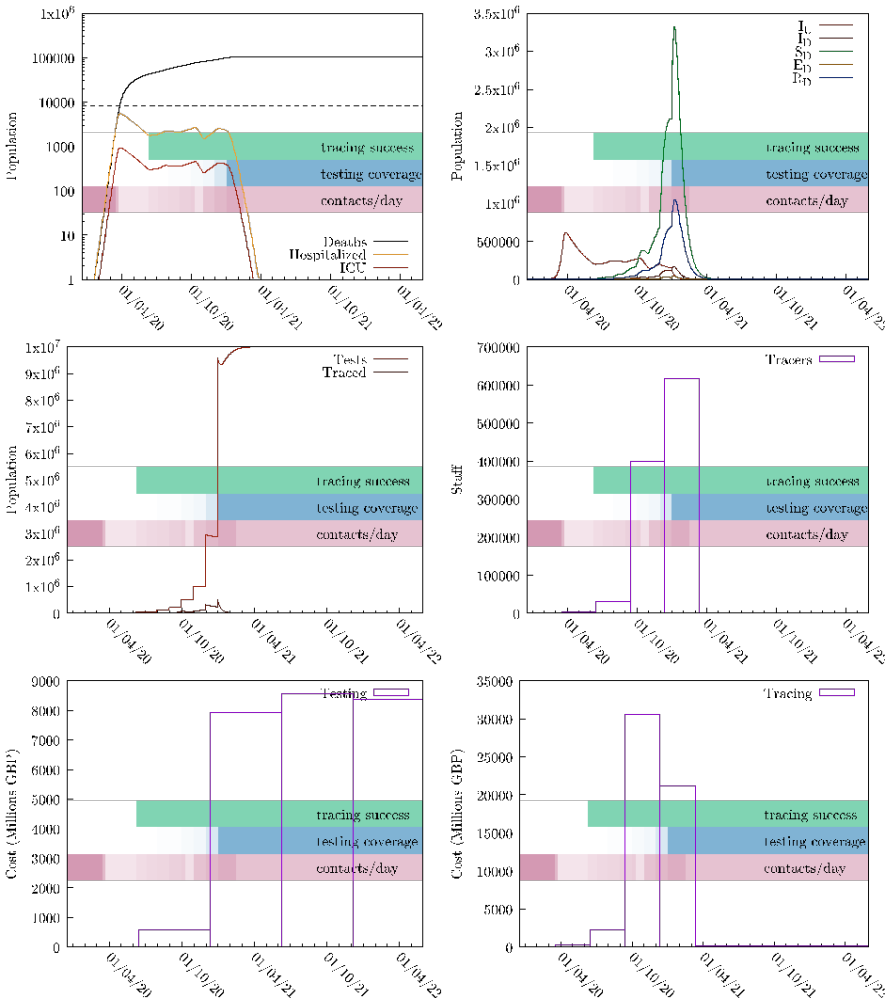


Figure S5 Targeted TTI trajectory

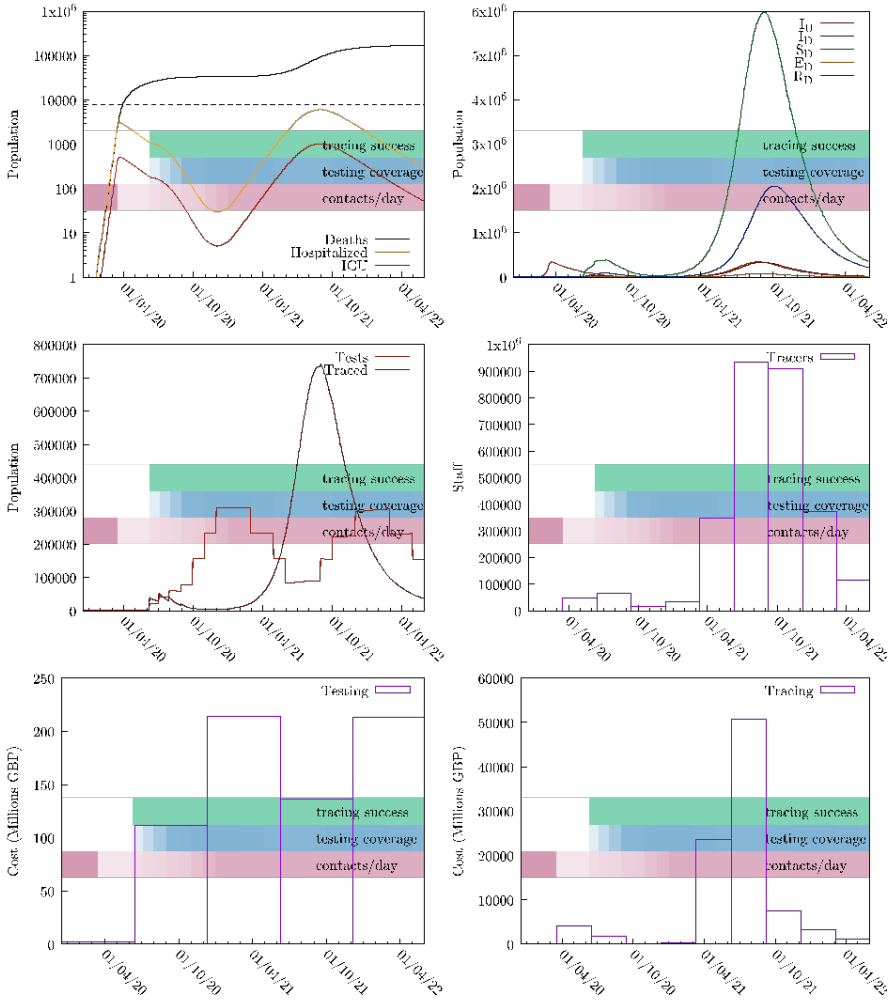


Figure S6 Targeted TTI Face Coverings trajectory

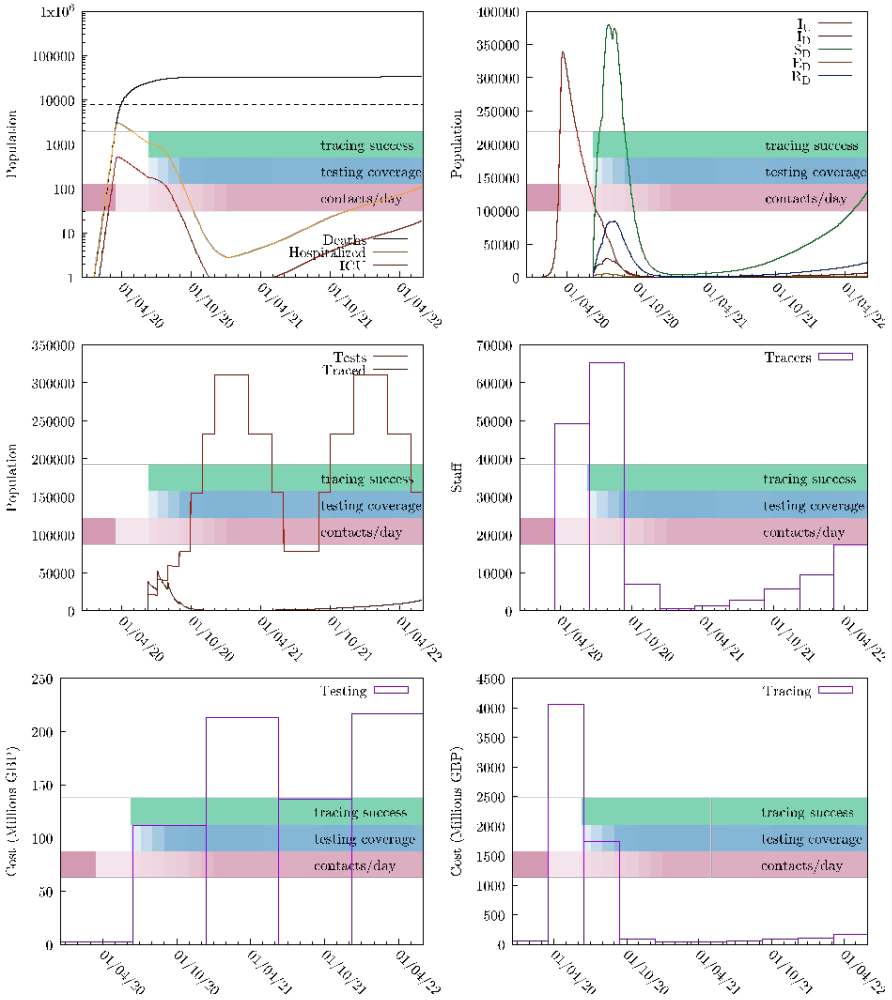


Figure S7 Targeted TTI Face Coverings Lockdown Triggers trajectory

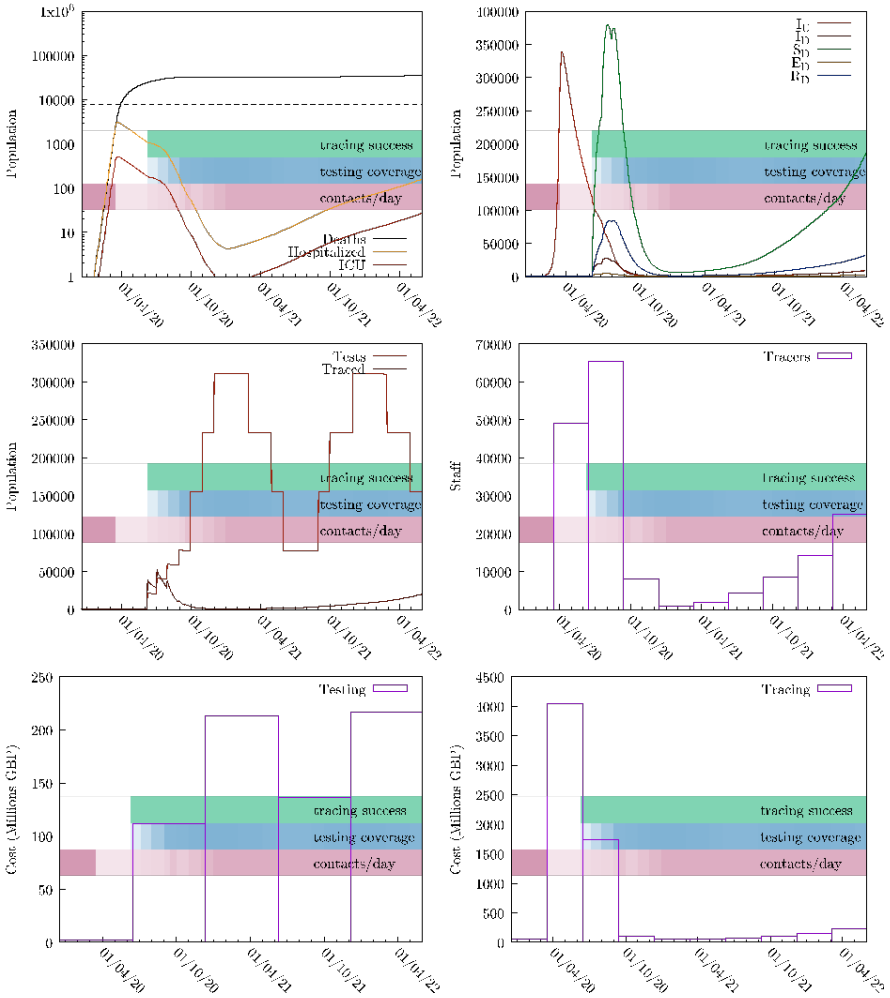


Table S7 Full Scenario Results

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	136,946	307,549	172,839	140,486	*232,131*	*46,566*	*47,987*
ICU cases	31,676	71,137	39,978	32,495	*53,693*	*10,771*	*11,100*
Hospital (non-ICU) cases	179,498	403,109	226,543	184,137	*304,258*	*61,034*	*62,898*
Non-hospital cases	12,101,530	27,177,179	15,273,265	12,414,342	*20,512,759*	*4,114,862*	*4,240,483*
NHS costs (£bn)	1.0	2.3	1.3	1.0	*1.7*	*0.3*	*0.4*
Reduction in GDP (£bn)	1,177.8	594.8	594.8	812.7	*601.6*	*601.6*	*597.0*
Public Health costs (£bn):	0.0	260.1	120.9	80.7	*93.3*	*7.1*	*7.3*
of which: Testing total costs (£bn)	0.0	25.2	25.4	25.4	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	0.0	234.9	95.6	55.3	*92.6*	*6.5*	*6.6*

Table S8 PTTI results

Comparison	Universal PTTI relative to No TTI Lockdown Triggers	Universal PTTI Face Coverings relative to No TTI Lockdown Triggers	Universal PTTI Face Coverings Lockdown Triggers relative to No TTI Lockdown Triggers	*Targetted TTI relative to No TTI Lockdown Triggers*	*Targeted PTTI Face Coverings relative to No TTI Lockdown Triggers*	*Targeted PTTI Face Coverings Lockdown Triggers relative to No TTI Lockdown Triggers*
Deaths	170,603	35,893	3,540	95,185	-90,381	-88,959
ICU cases	39,461	8,302	819	22,017	-20,905	-20,576
Hospital (non-ICU) cases	223,612	47,045	4,640	124,761	-118,463	-116,600
Non-hospital cases	15,075,649	3,171,735	312,812	8,411,229	-7,986,668	-7,861,047
NHS costs (£bn)	1	0	0	1	-1	-1
Reduction in GDP (£bn)	-583	-583	-365	-576	-576	-581
Public Health costs (£bn):	260	121	81	93	7	7
of which: Testing total costs (£bn)	25	25	25	1	1	1
Tracing total costs (£bn)	235	96	55	93	6	7

Lockdown triggers

Three scenarios have subsequent lockdowns triggered when daily new infections increase above 40,000 per day. Comparing these to their counterpart scenarios without triggers for lockdowns we see that additional lockdowns were triggered when there were no interventions (No TTI Lockdown Triggers, Figure S1), and when there was Universal PTTI with face coverings (Untargeted PTTI Face Coverings Lockdown Triggers, one additional lockdown, Figure S4). Additional lockdowns were not triggered in the Targeted PTTI Face Coverings Lockdown Trigger scenario (Figure S7). Scenarios with lockdown triggers resulted in additional reduction in GDP compared to the same scenario without lockdown triggers.

Face coverings

Including face coverings has a large estimated beneficial impact when universal testing, tracing and isolation is scaled-up to weekly testing during phased lockdown release (Universal PTTI Face Coverings relative to Universal PTTI, ~134,000 deaths averted, Table S9) and when targeted testing of symptomatic only and tracing and isolation is scaled-up during phased lockdown release (Targeted PTTI Face Coverings relative to Targeted PTTI, ~186,000 deaths averted, Table S9).

Untargeted large-scale testing vs. targeted testing of symptomatics

Table S10 shows that universal testing results in more deaths than targeted testing. This is because we assume it will take longer to scale up (to the end of December 2020) during which time contacts per day will increase sufficiently to cause a second epidemic wave that is not stopped by universal PTTI (Figures S2–S4). We assume targeted TTI is scaled-up in time (by end of August 2020) to prevent a secondary epidemic wave via rapid tracing and isolation of a sufficient proportion of all contacts of those who test positive. Universal testing has £27bn greater testing costs than targeted testing and, because it results in more cases (and identifies a greater proportion of them), greater tracing costs too.

Table S9 Face coverings results

Comparison	Universal PTTI Face Coverings relative to Universal PTTI	*Targeted PTTI Face Coverings relative to Targeted PTTI*
Deaths	-134,710	-185,566
ICU cases	-31,159	-42,922
Hospital (non-ICU) cases	-176,566	-243,224
Non-hospital cases	-11,903,914	-16,397,897
NHS costs (£bn)	-1	-1
Reduction in GDP (£bn)	0	0
Public Health costs (£bn):	-139	-86
of which: Testing total costs (£bn)	0	0
Tracing total costs (£bn)	-139	-86

Table S10 Universal large-scale testing vs. targeted testing of symptomatic people

Comparison	Universal PTTI relative to Targeted PTTI	Universal PTTI Face Coverings relative to Targeted PTTI Face Coverings	*Universal PTTI Face Coverings Lockdown Triggers relative to Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	75,417	126,273	92,499
ICU cases	17,444	29,207	21,395
Hospital (non-ICU) cases	98,851	165,509	121,240
Non-hospital cases	6,664,420	11,158,403	8,173,859
NHS costs (£bn)	1	1	1
GDP reduction (£bn)	-7	-7	216
Public Health costs (£bn):	167	114	73
of which: Testing total costs (£bn)	25	25	25
Tracing total costs (£bn)	142	89	49

Sensitivity Analysis

Table S11 Values used in Sensitivity Analyses

		Values used in Sensitivity Analysis	
Parameter	**Base case value**	**Low value**	**High value**
GDP Reduction for time spent in lockdown	25%	10%	40%
Face coverings effectiveness in reducing transmission (Beta)	15%	5%	30%
Percentage of infections that are symptomatic (this parameter is only used in Targeted PTTI scenarios)	50%	30%	50%
		Alternative value	
Length of infectious period	7 days	5 days	
Incubation (latent) period	5 days	(3 days)	

Table S12 Results with GDP 10% reductions

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Reduction in GDP (£bn)	471.1	237.9	237.9	325.1	*240.7*	*240.7*	*238.8*

Figure S8 Summary results with GDP 10% reductions

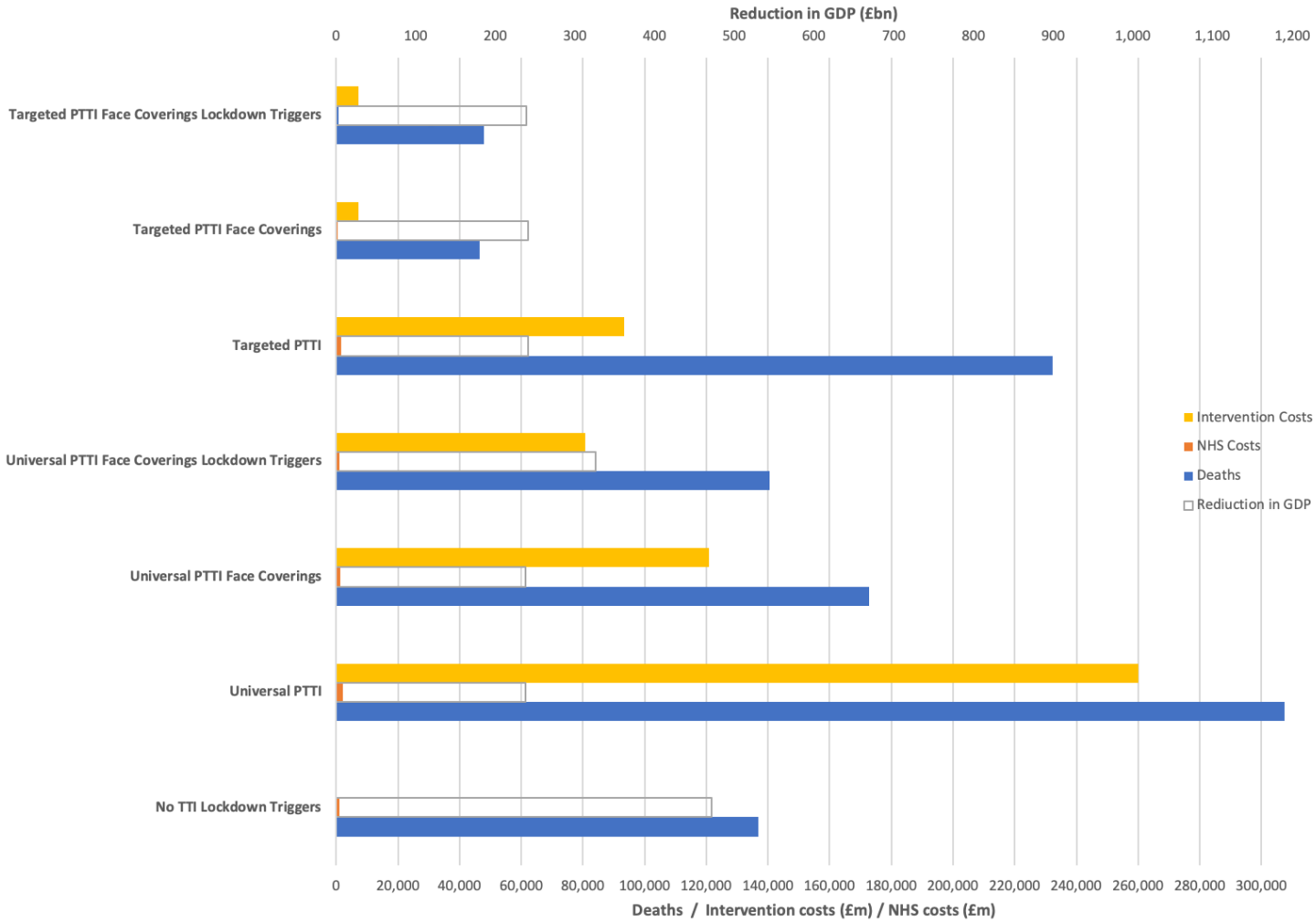


Table S13 Results with GDP 40% reductions

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Reduction in GDP (£bn)	1,884.6	951.7	951.7	1,300.3	*962.6*	*962.6*	*955.2*

Figure S9 Summary results with GDP 40% reductions

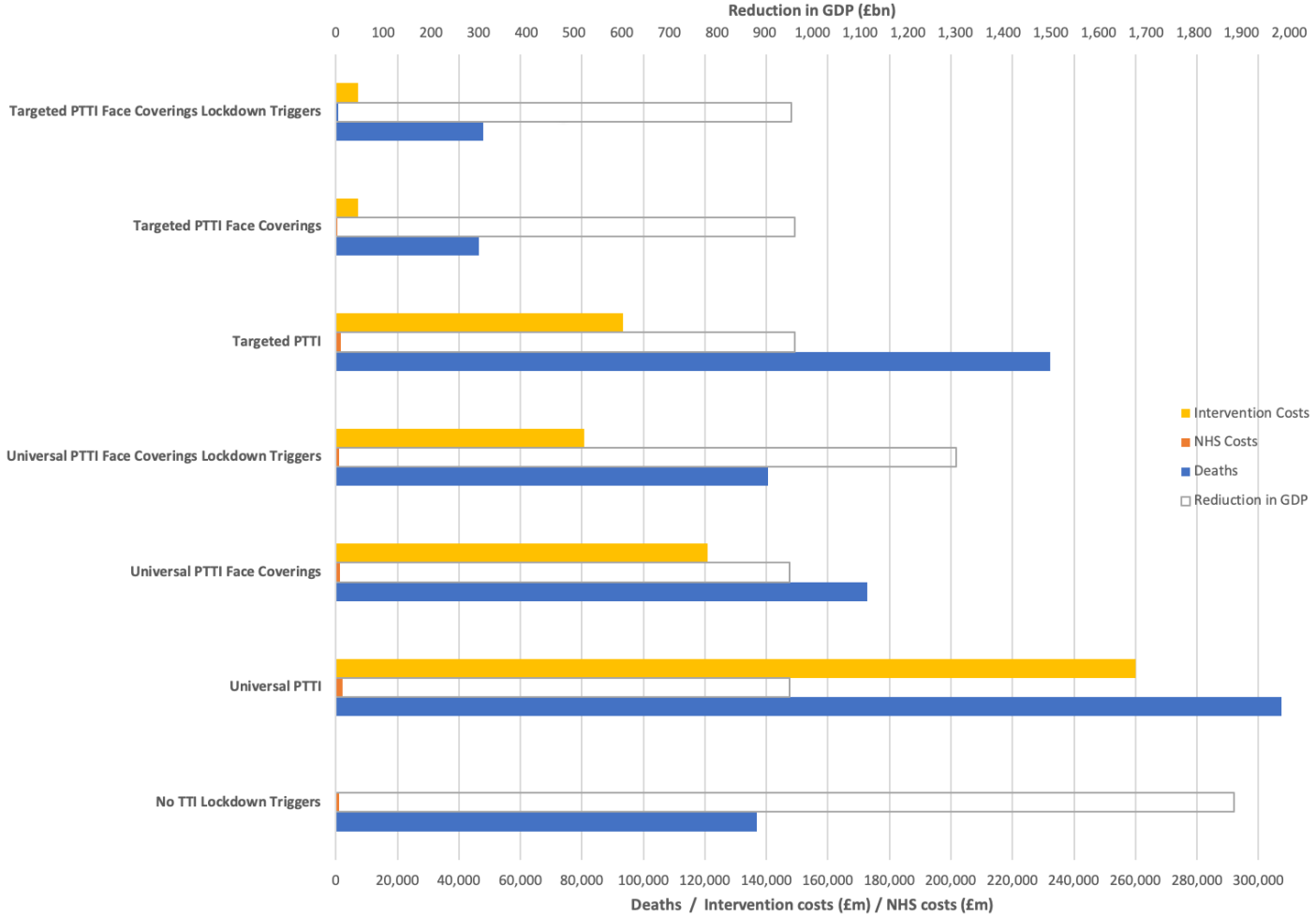


Table S14 Results with Face coverings 5% effective

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings Lockdown Triggers	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	136,946	307,549	260,323	146,563	*232,131*	*183,334*	*49,436*
ICU cases	31,676	71,137	60,214	33,900	*53,693*	*42,406*	*11,435*
Hospital (non-ICU) cases	179,498	403,109	341,210	192,102	*304,258*	*240,299*	*64,797*
Non-hospital cases	12,101,530	27,177,179	23,004,012	12,951,303	*20,512,759*	*16,200,722*	*4,368,542*
NHS costs (£bn)	1.0	2.3	1.9	1.1	*1.7*	*1.3*	*0.4*
Reduction in GDP (£bn)	1,177.8	594.8	594.8	827.8	*601.6*	*601.6*	*780.4*
Public Health costs (£bn):	0.0	260.1	207.2	80.3	*93.3*	*59.2*	*7.6*
of which: Testing total costs (£bn)	0.0	25.2	25.2	25.4	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	0.0	234.9	182.0	54.8	*92.6*	*58.5*	*6.9*

Figure S10 Summary results with Face coverings 5% effective

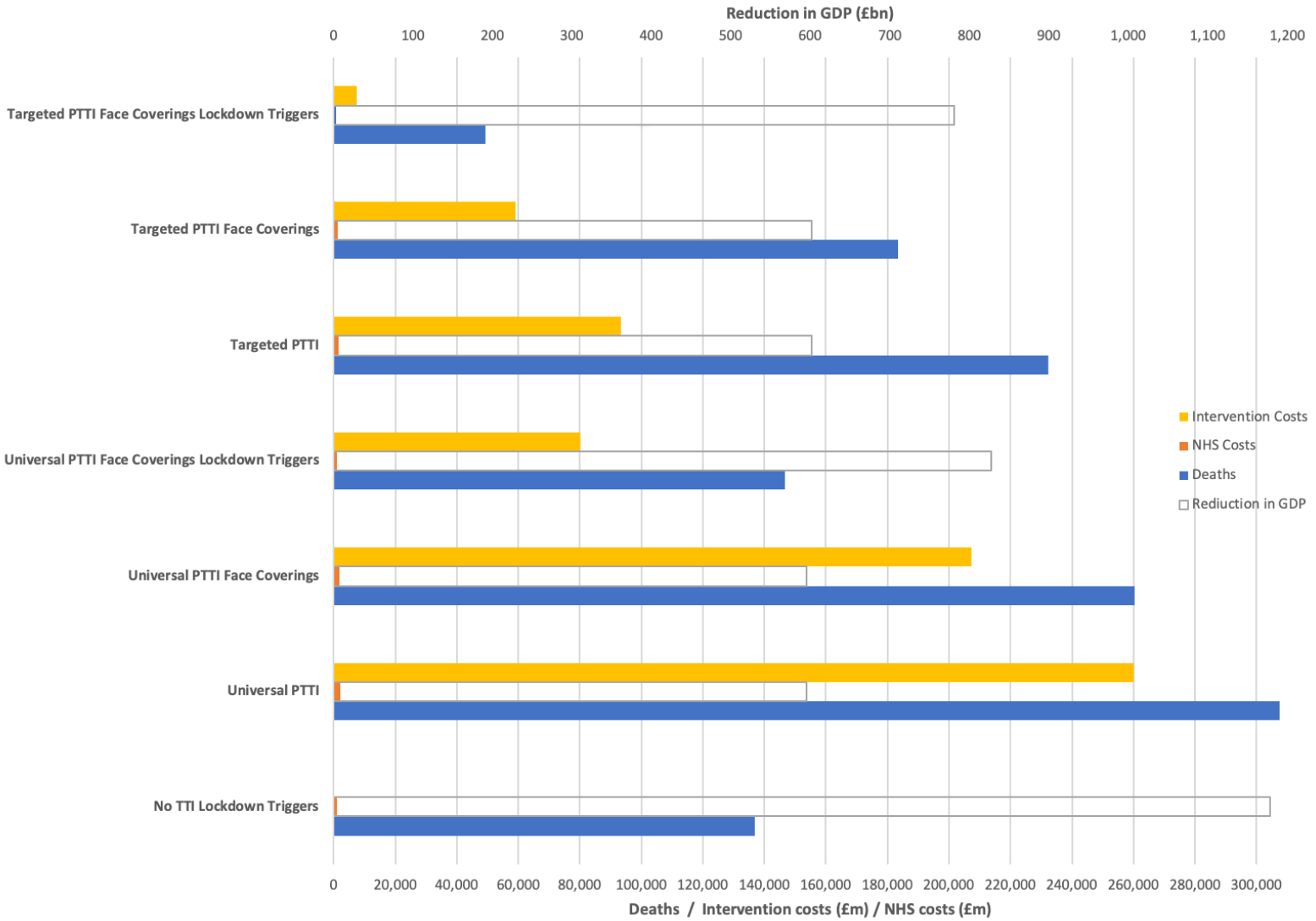


Table S15 Results with Face coverings 30% effective

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	136,946	307,549	102,939	102,932	*232,131*	*43,074*	*43,074*
ICU cases	31,676	71,137	23,810	23,809	*53,693*	*9,963*	*9,963*
Hospital (non-ICU) cases	179,498	403,109	134,923	134,915	*304,258*	*56,458*	*56,458*
Non-hospital cases	12,101,530	27,177,179	9,096,383	9,095,818	*20,512,759*	*3,806,347*	*3,806,347*
NHS costs (£bn)	1.0	2.3	0.8	0.8	*1.7*	*0.3*	*0.3*
Reduction in GDP (£bn)	1,177.8	594.8	594.8	810.9	*601.6*	*601.6*	*601.6*
Public Health costs (£bn):	0.0	260.1	39.4	39.4	*93.3*	*6.8*	*6.8*
of which: Testing total costs (£bn)	0.0	25.2	25.5	25.5	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	0.0	234.9	13.9	13.9	*92.6*	*6.1*	*6.1*

Figure S11 Summary results with Face coverings 30% effective

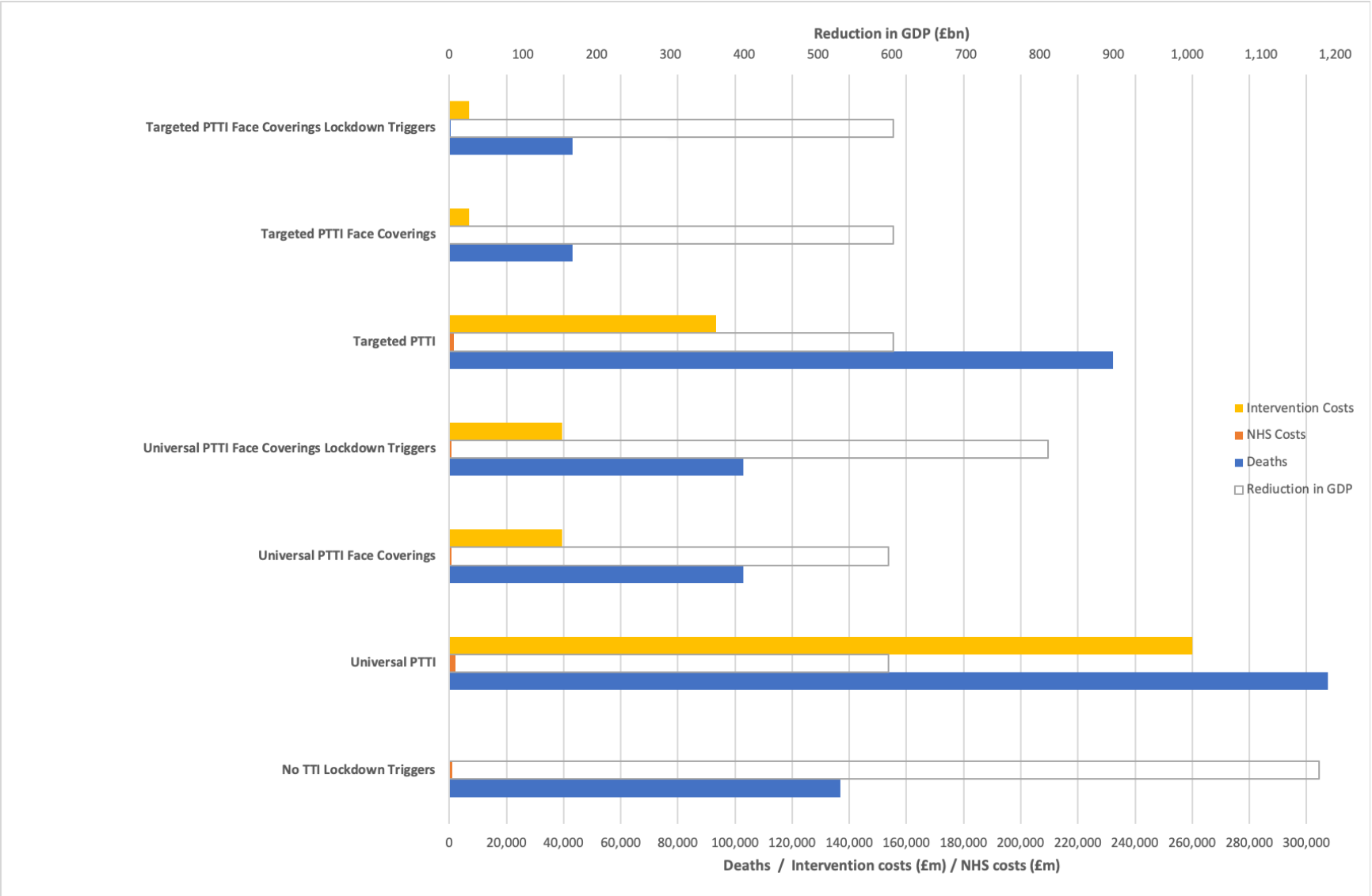


Table S16 Results with 30% Symptomatic

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	136,946	307,549	172,839	140,486	*372,345*	*292,207*	*55,959*
ICU cases	31,676	71,137	39,978	32,495	*86,125*	*67,588*	*12,944*
Hospital (non-ICU) cases	179,498	403,109	226,543	184,137	*488,039*	*383,000*	*73,347*
Non-hospital cases	12,101,530	27,177,179	15,273,265	12,414,342	*32,903,052*	*25,821,451*	*4,944,943*
NHS costs (£bn)	1.0	2.3	1.3	1.0	*2.7*	*2.1*	*0.4*
Reduction in GDP (£bn)	1,177.8	594.8	594.8	812.7	*601.6*	*601.6*	*836.8*
Public Health costs (£bn):	0.0	260.1	120.9	80.7	*208.0*	*117.7*	*6.9*
of which: Testing total costs (£bn)	0.0	25.2	25.4	25.4	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	0.0	234.9	95.6	55.3	*207.3*	*117.0*	*6.2*

Figure S12 Summary results with 30% symptomatic

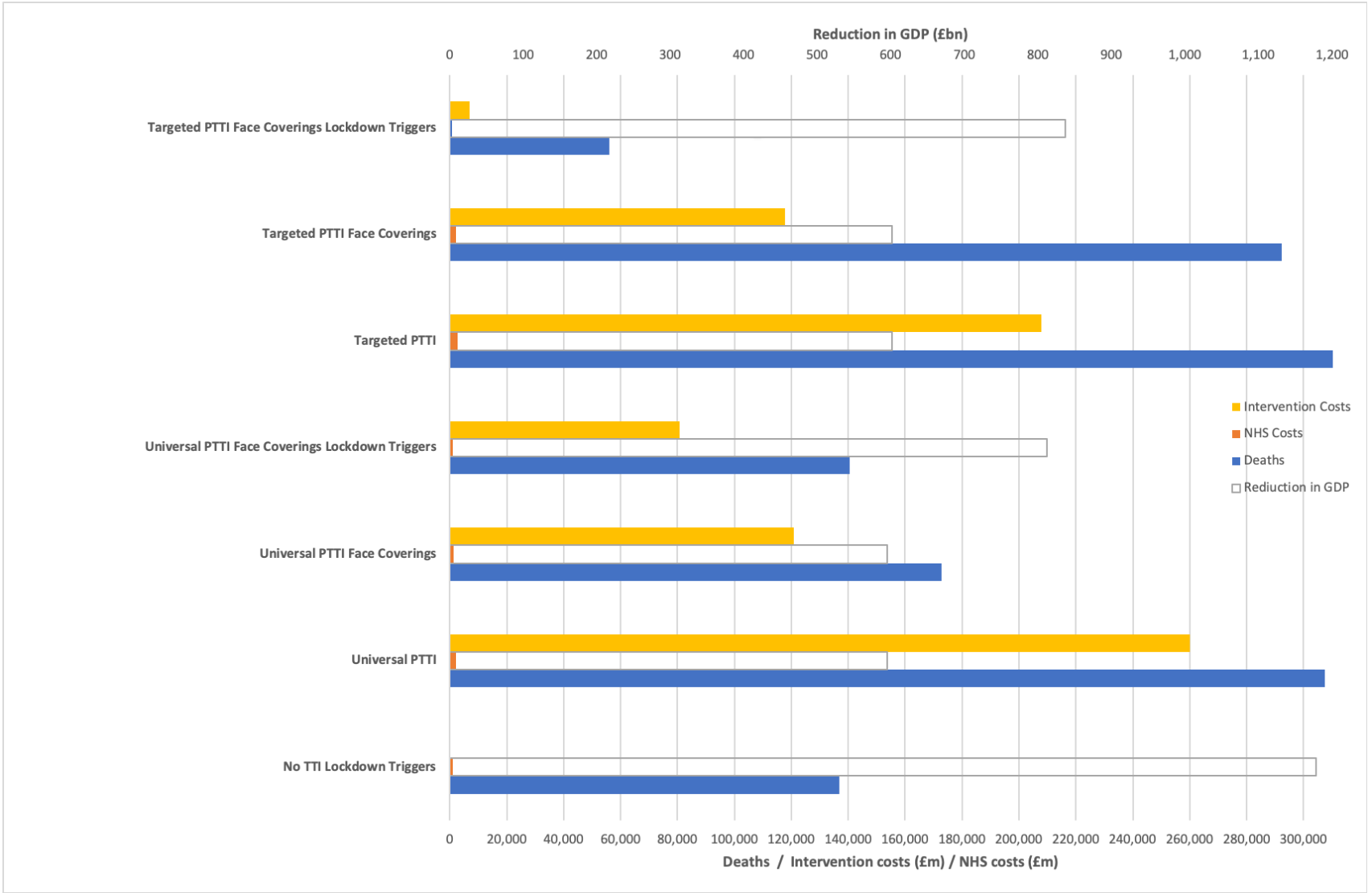


Table S17 Results with 80% Symptomatic

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	136,946	307,549	172,839	140,486	*41,323*	*41,059*	*41,059*
ICU cases	31,676	71,137	39,978	32,495	*9,558*	*9,497*	*9,497*
Hospital (non-ICU) cases	179,498	403,109	226,543	184,137	*54,163*	*53,817*	*53,817*
Non-hospital cases	12,101,530	27,177,179	15,273,265	12,414,342	*3,651,630*	*3,628,285*	*3,628,285*
NHS costs (£bn)	1.0	2.3	1.3	1.0	*0.3*	*0.3*	*0.3*
Reduction in GDP (£bn)	1,177.8	594.8	594.8	812.7	*601.6*	*601.6*	*601.6*
Public Health costs (£bn):	0.0	260.1	120.9	80.7	*7.5*	*7.5*	*7.5*
of which: Testing total costs (£bn)	0.0	25.2	25.4	25.4	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	0.0	234.9	95.6	55.3	*6.9*	*6.9*	*6.9*

Figure S13 Summary results with 80% symptomatic

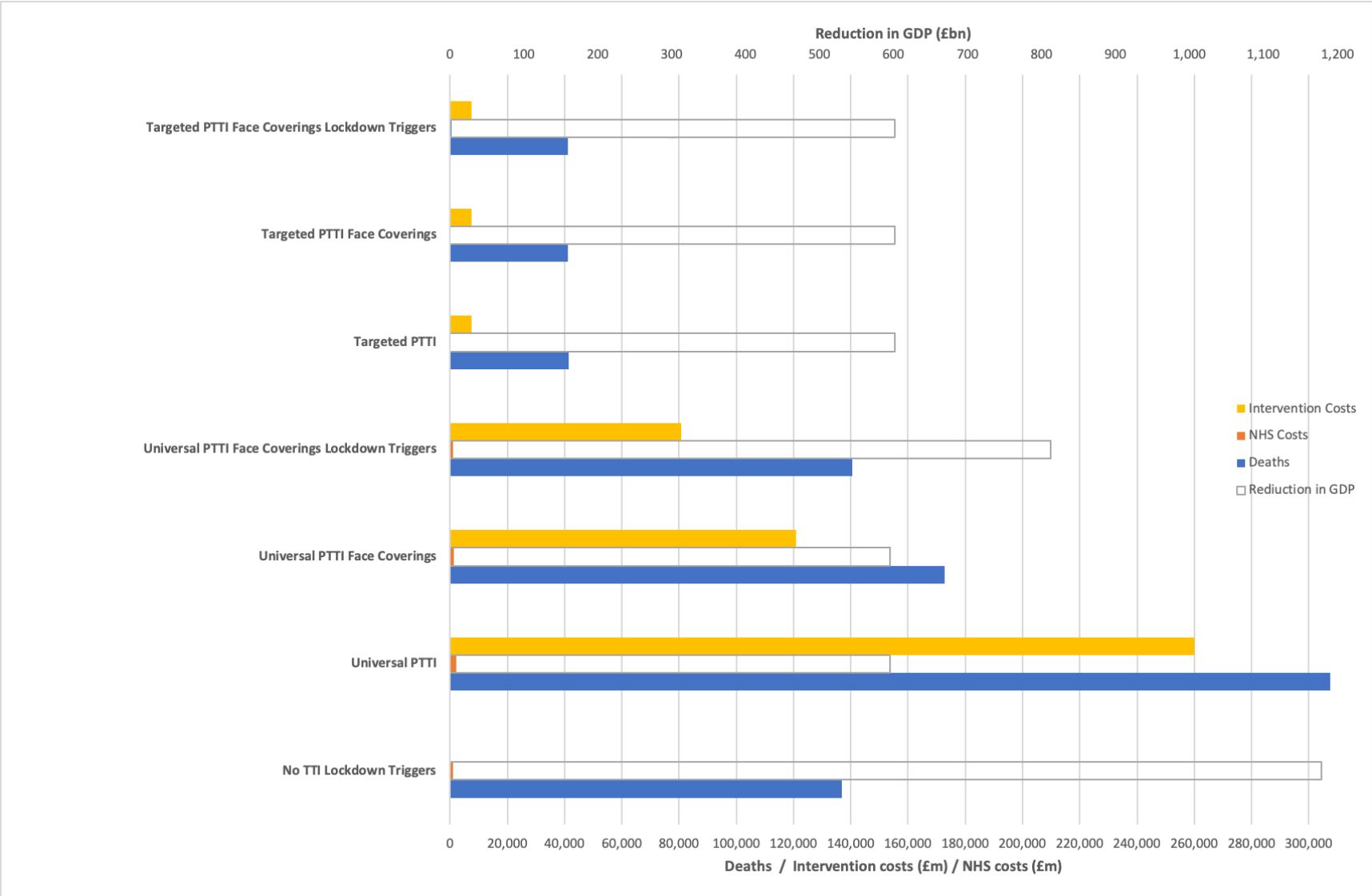


Table S18 Results with 5 day infectious period

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	147,213	378,831	203,280	138,839	*328,539*	*222,978*	*36,720*
ICU cases	34,051	87,625	47,019	32,114	*75,992*	*51,575*	*8,494*
Hospital (non-ICU) cases	192,955	496,541	266,442	181,978	*430,622*	*292,261*	*48,130*
Non-hospital cases	13,008,820	33,476,214	17,963,229	12,268,771	*29,032,054*	*19,703,876*	*3,244,877*
NHS costs (£bn)	1.1	2.8	1.5	1.0	*2.4*	*1.6*	*0.3*
Reduction in GDP (£bn)	1,167.4	594.8	594.8	831.3	*601.6*	*601.6*	*789.9*
Public Health costs (£bn):	0.0	173.7	98.0	46.1	*149.3*	*67.0*	*5.8*
of which: Testing total costs (£bn)	0.0	25.3	25.3	25.5	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	0.0	148.5	72.6	20.6	*148.6*	*66.4*	*5.1*

Figure S14 Summary results with 5 day infectious period

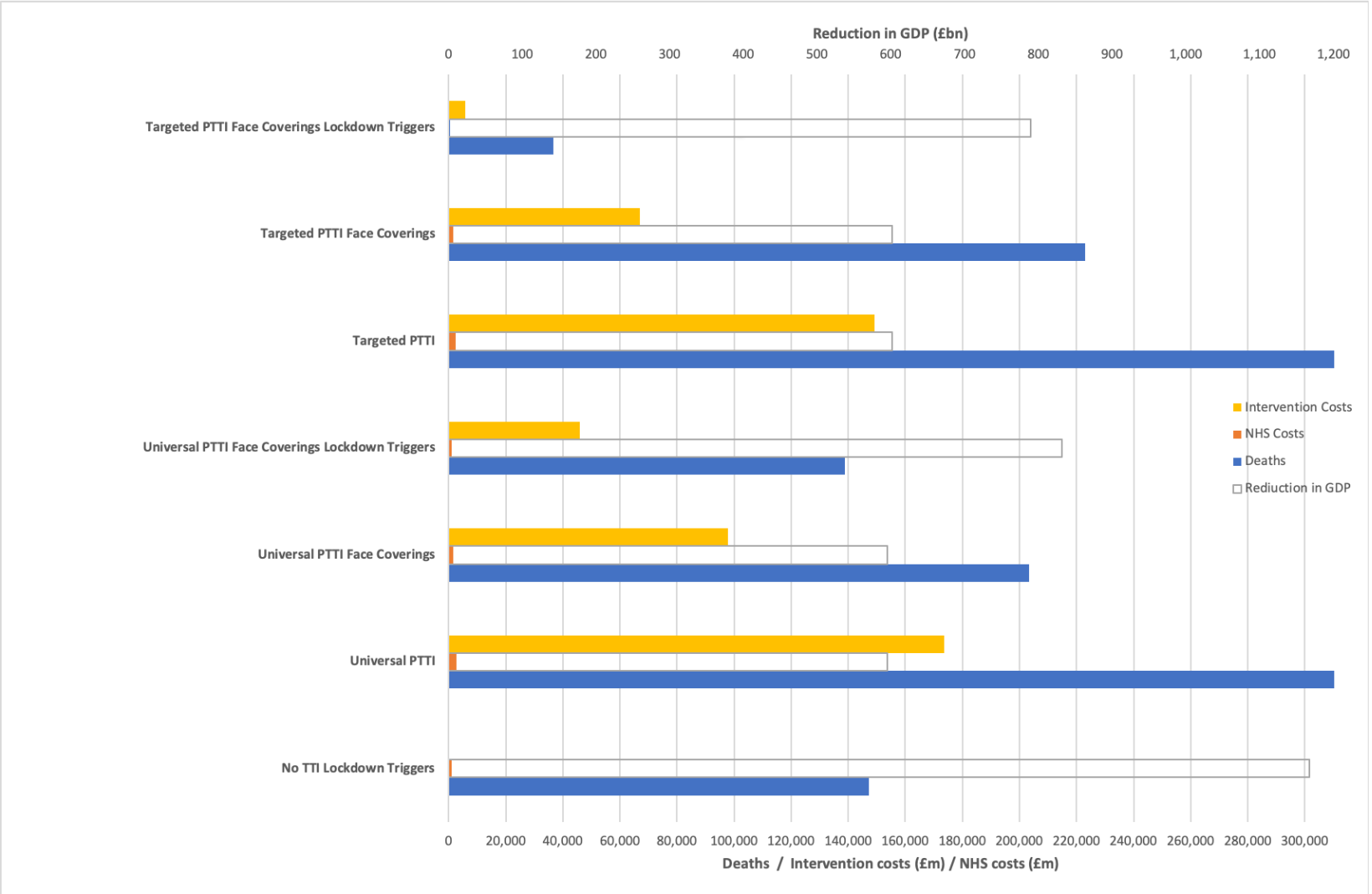
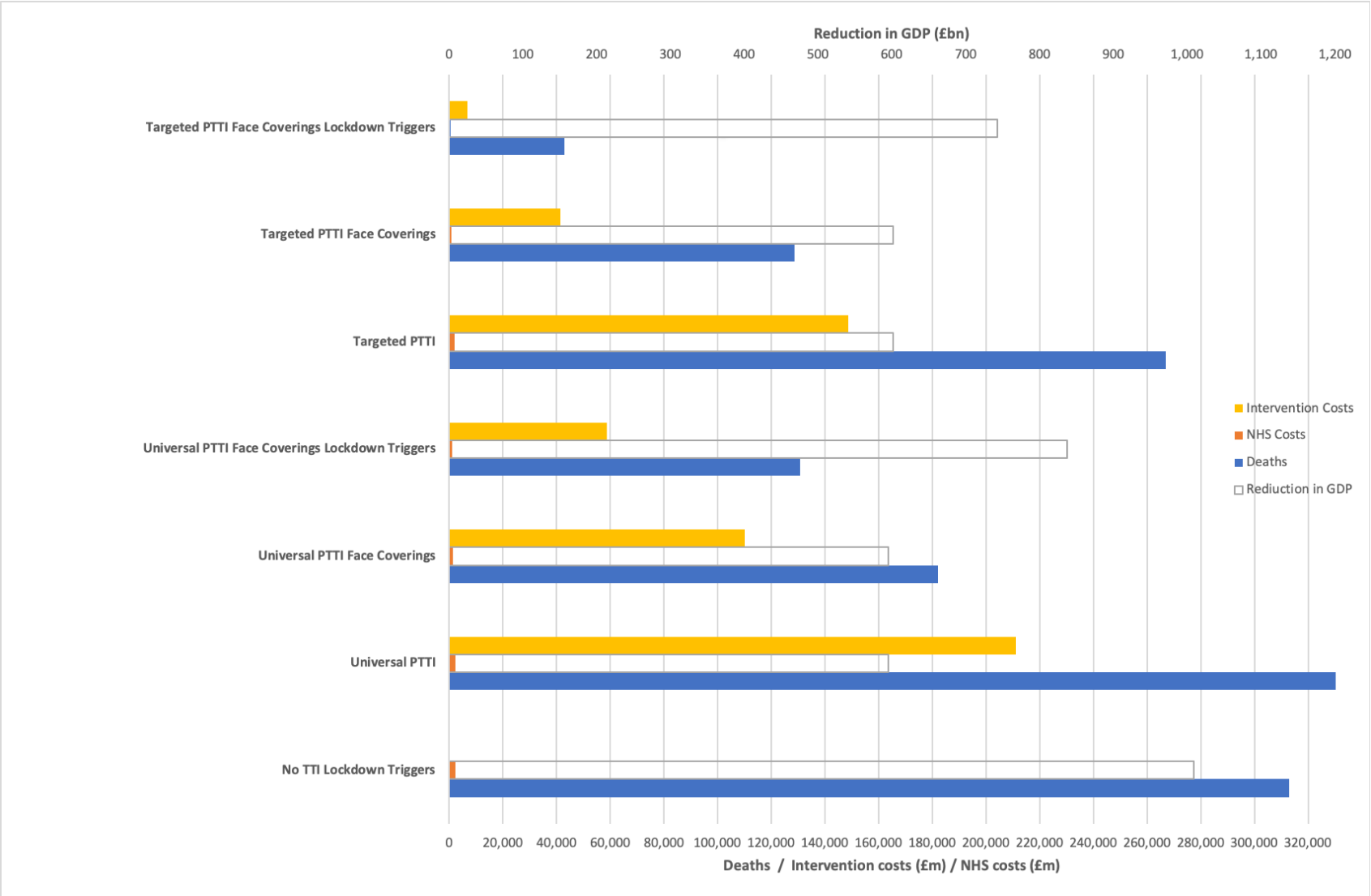


Table S19 Results with 3 day latent period

To 31st May 2022	No TTI Lockdown Triggers	Universal PTTI	Universal PTTI Face Coverings	Universal PTTI Face Coverings Lockdown Triggers	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*
Deaths	313,093	331,896	182,190	130,648	*266,910*	*128,612*	*42,780*
ICU cases	72,419	76,769	42,141	30,219	*61,737*	*29,748*	*9,895*
Hospital (non-ICU) cases	410,376	435,022	238,800	171,243	*349,843*	*168,574*	*56,072*
Non-hospital cases	27,667,112	29,328,666	16,099,633	11,545,019	*23,586,043*	*11,365,041*	*3,780,336*
NHS costs (£bn)	2.3	2.4	1.3	1.0	*2.0*	*0.9*	*0.3*
Reduction in GDP (£bn)	1,009.1	594.8	594.8	837.3	*601.6*	*601.6*	*742.7*
Public Health costs (£bn):	0.0	211.2	110.0	58.7	*148.7*	*41.4*	*6.9*
of which: Testing total costs (£bn)	0.0	25.2	25.3	25.5	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	0.0	186.0	84.7	33.2	*148.0*	*40.7*	*6.2*

Figure S15 Summary results with 3 day latent period



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