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 300,000 reported cases and over 43,000 deaths as of 24th June 2020. With the slower increase in reported cases and deaths over the last few weeks compared to earlier in the epidemic, the UK is starting to relax the physical

restrictions ('lockdown') that have been imposed since 23 March 2020. Since June, 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 masks, are expected to be impactful, there is no conclusive evidence of which approach is likely to achieve the most appropriate balance between health benefits and costs. 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 population-scale test-trace-isolate (PTTI) strategies with a deterministic mathematical model for SARS-CoV-2 transmission that accurately captures tracing and isolation of contacts of individuals exposed, infectious, and diagnosed with the virus. We 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 derived from publicly available data, and the model was calibrated to reported deaths associated with COVID-19. We modelled 16 scenarios in total. The first 10 comprised five with lockdown triggers for subsequent lockdown periods (>40,000 active infections) and lockdown releases (<10,000 active infections), and five corresponding scenarios without triggers, namely: No TTI; testing the whole population every week, following June–August 2020 lockdown release (Untargeted PTTI), ; this scenario with mandatory use of face coverings (Untargeted PTTI Face Coverings); and these two scenarios replacing untargeted PTTI with testing of symptomatic people only (Targeted PTTI and Targeted PTTI Face Coverings). The final six scenarios looked at: whole-population weekly testing to suppress the epidemic with lower tracing success (Untargeted PTTI 0%/30% Tracing Success Face Coverings Lockdown Triggers), switching from Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers to targeted testing after two months when it may suppress the epidemic (Untargeted to Targeted PTTI Face Coverings Lockdown Triggers), and targeted testing with lower tracing success (Targeted PTTI 30%/40%/50% Tracing Success Face Coverings Lockdown Triggers). A deterministic sensitivity analysis varied parameters for GDP loss, face covering effectiveness, proportion of infections that are symptomatic, incubation period, and infectious period.

Findings

Targeted testing of symptomatic people only plus tracing and isolation, with a mandatory face coverings policy and subsequent lockdown triggered to enable PTTI to suppress the epidemic (Targeted PTTI Face Coverings Lockdown Triggers), results in the fewest deaths (~60,000) and has the lowest intervention costs (~£12bn). The additional lockdown results in total reduction in GDP of ~£537bn over a two-year period, less than half the cost to the economy of subsequent lockdowns triggered in a scenario without PTTI (No TTI Lockdown Triggers: ~£1172bn reduction in GDP; ~112,000 deaths). In summer months, with lower cold and flu prevalence, approximately 75,000 symptomatic people per day need to be tested for this strategy to work, assuming 72% of their contacts are traced within 2 days. Untargeted testing of everyone every week, if it were feasible, may work without tracing, but at a higher cost (Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers: ~£28bn intervention costs). This cost could be reduced by switching to targeted testing after the epidemic is suppressed (Untargeted to Targeted PTTI Face Coverings Lockdown Triggers), though we note the epidemic could be suppressed with targeted testing itself providing tracing and isolation has at least a 50% success rate (Targeted PTTI 50% Tracing Success Face Coverings Lockdown Triggers).

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

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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 2 June 2020 with the terms "(Econom* OR cost* OR benefit* OR "public health") AND (Covid* OR SARS-Cov-2) AND (evalu* OR interven* OR test* OR trac* OR TTI OR exit* OR strateg*)" and found 55 unique articles published in 2020, nine of which have a focus on country-level COVID-19 strategy. Four of these used modelling and explored different strategies, but none 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). Unlike previous models, our study focuses on strategies that would not require further lockdowns, and includes combinations of population-scale contact tracing, early case detection, SARS-CoV-2 viral testing, isolation of cases and contacts, and use of face coverings. Unlike previous studies, we explore a wide range of strategies. The feasibility of such strategies at population scale has been demonstrated under lockdown in Wuhan, China and Vo, Italy, and without lockdown in Taiwan, South Korea, and Vietnam. Population-scale tracing, testing, and isolation was originally proposed for the UK by Julian Peto, one of the co-authors here, and has recently been proposed for the USA by Harvard and Paul Romer.

Added value of this study
We show that a targeted population-scale testing, tracing, and isolation strategy can prevent tens of thousands of COVID-19 deaths 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).

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. With the UK starting to relax restrictions from early June, and some schools in England readmitting some students as the first step of reopening society, it is important to assess the best way to keep infections down and prevent subsequent epidemic waves..

Recent estimates suggest that only 5.4% of the population of England (95% confidence interval [CI]: 4.3% to 6.5%) had been infected with SARS-CoV-2 as of 13 June 2020,[3] with significant regional and demographic variation. This level of presumed immunity is a long way from the roughly 60% required for herd immunity without "overshoot".[4] Overshoot involves exposing more people to the disease than is needed for herd immunity, and could increase the proportion to around 80% depending on the number of active cases[5] as the threshold is approached. Consequently, if we consider only the binary choice of lockdown or remaining open, we are likely to need lockdown for three of every four months[2,6] (or four of every six months)[2,6] until there is a vaccine to safely induce herd immunity, or highly effective drugs to prevent most deaths. Without 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.[1]

Mathematical models can be used to predict COVID-19 epidemic trends following relaxation of lockdown.1,2 To date, the COVID-19 models focused on testing, tracing, and isolation (TTI) to keep the epidemic suppressed have considered the topic on its own. In contrast, this paper 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. We use this combined model to explore 16 different PTTI scenarios and identify the optimal strategy to safely reopen the UK economy whilst protecting the public from further COVID-19 outbreaks. We examine both the effects and the costs of combinations of various strategies, including targeted testing of symptomatic people only as well as regular testing of a proportion of all people, with or without contact tracing and the use of face coverings.

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

together with isolation of these contacts for 14 symptom-free days, might ensure the epidemic is suppressed.

To our knowledge, this is the first paper to examine the effects of changing interventions and gradually building the required capacity for testing and tracing. We detail the resources required for the PTTI interventions, including the capacity required to end the COVID-19 epidemic in the UK and keep the virus suppressed until there is a vaccine or highly effective treatment. We compare this to alternatives of an unmitigated epidemic, or intermittent lockdown triggered by resurgence of infection, without PTTI. In order to identify potentially feasible PTTI approaches, we consider cases where outbreaks have been successfully suppressed using similar strategies, albeit in diverse socio-cultural and political environments, and often in combination with physical distancing interventions (Panel 1).

Panel 1: 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.[11] 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[12] 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.[11]

South Korea - South Korean contact tracers make widespread use of technology, using data from GPS, credit/debit cards, gyms, and public transport, as well as CCTV and interviews.[13] All traced contacts are tested, and positive cases are 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.[14]

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

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

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

Ghana - Many in the global health community feared that African countries would be most severely hit by COVID-19, due to their weaker health systems and lower levels of economic development. However, many places have fared relatively well. Ghana in particular has been highlighted as a success, with a total of ~10,000 confirmed cases and 44 deaths in a population of over 31 million.[22,23] Although it did implement a 21-day lockdown, its success has been partly attributed to 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.[24]

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 modeldescribed in detail elsewhere.[25] SEIR-TTI extends the classic SEIR cohorts of susceptible (S), exposed to the virus but not infectious (E), infected and infectious (I), and removed (R) populations 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.[25] This produces a realistic representation of the effect of isolating susceptible, exposed, and infectious individuals on disease propagation, and of unnecessary isolation of recovered individuals on costs.

The SEIR-TTI is shown schematically in Figure S1. The possible transitions between cohorts are indicated with arrows. The overall progression is from susceptible (S), to exposed (E), to infectious (I), and finally to removed (R) states. Within each of these states, an individual can be unconfined or isolated. Infectious (I) individuals who are unconfined may be tested and become isolated. An individual in any state 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 PTTI. 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/). 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. We construcedt a scenario fixing β while allowing the contact rate, c, to vary freely in intervals separated by policy changes at known times (16th and 23rd of March, 16th of May, 1st of June). This showed clearly that the data is of poor quality before the end of March and that the effective reproduction number has been approximately 0.9 since then. Using the COMIX survey to find c, we estimated β to be 0.042. We conducted a sensitivity analysis on this value. Given this value for β, we ascertained that, if the epidemic in the UK was seeded by a single individual, and if the outbreak proceeded deterministically according to our model, that individual would have had to be infectious in late December or early January. We have chosen a "seed date" of the 18th of December as consistent with the data given this model and initial

conditions. However, this should not be construed as a claim about the origins and early history of the epidemic in the UK; this work is intended to explore possible future scenarios and not to investigate the past.

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 modelled 16 scenarios in total (Panel 2). The first 10 were decided *a priori*: five with and five without triggers for subsequent lockdown periods and lockdown releases. The five core scenarios are: the baseline with no testing and tracing (No TTI); scale-up of testing to the whole population every week, with tracing, with the current lockdown release (Untargeted PTTI) ; this scenario with mandatory use of face coverings (Untargeted PTTI Face Coverings); and the previous two scenarios replacing untargeted population-scale testing with testing of symptomatic people only and tracing (Targeted PTTI and Targeted PTTI Face Coverings). The final six scenarios were run following discussion of the findings from the first 10 scenarios to explore emerging policy questions: whether testing the whole population every week can suppress the epidemic with lower tracing success (Untargeted PTTI 0% Tracing Success, 30% Tracing Success) and can be switched to targeted testing after two months when it may suppress the epidemic (Untargeted to Targeted PTTI Face Coverings Lockdown Triggers), and whether targeted testing can suppress the epidemic with lower tracing success (Targeted PTTI 30% Tracing Success, 40% Tracing Success, 50% Tracing Success)

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),[30–37] and an assumption that they would be used in 20–60% of contacts occurring in the modelled scenario trajectories[38,39]. 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 wer met (<10,000 cases to release, and >40,000 cases to lock down again). Scenarios without lockdown and release triggers diverge from 13 May when different interventions are set (Panel 1; see scenario .yaml files here for full details). Lockdown release triggers were set for lockdown release to 80% of pre-pandemic contacts after lockdown release (this is the same number of contacts as at the end of phased lockdown release).

Panel 2: Modelled scenarios

Scenario	description	date	$1/\theta$	χ	η	β	c0=11
Base part	Baseline trajectory to date, common	18-Dec-19	0	0	0	0.042	1

	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 and22 Dec. 16 March 2020: first weak measures announced to slow spread. 23 March: lockdown ordered.	16-Mar-20	0	0	0	0.042	0.7
		23-Mar-20	0	0	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 5–12th June. Entertainment venues to open 4 July	09-Jun-20	-	0	0	0.042	0.35
		04-Jul-20	-	0	0	0.042	0.6
		31-Jul-20	-	0	0	0.042	0.7
		31-Aug-20	-	0	0	0.042	0.8
Untargeted 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).	18-May-20	678	0.8	0.8	0.042	0.26
		09-Jun-20	226	0.8	0.8	0.042	0.35
		04-Jul-20	75.3	0.8	0.8	0.042	0.6
		31-Jul-20	22.6	0.8	0.8	0.042	0.7
		31-Aug-20	7	0.8	0.8	0.042	0.8
Untargeted PTTI Face Coverings	F**ace coverings added to Untargeted PTTI starting 4h July to coincide with entertainment venue opening. Reduce transmission (Beta) by 25%**	04-July-20				0.0315	
Targeted PTTI, Targeted PTTI Face Coverings	**Clinical case identification.** As Untargeted PTTI but with targeted testing of symptomatic cases identified clinically.	Parameters the same as Untargeted PTTI and Untargeted 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[40]), as explained in the footnote.[1] Prevalence of those symptomatic with colds or flu is varied throughout the year. A proportion of those symptomatic with cold, flu or COVID-19 (assumed not distinguishable from each other via clinical case identification) are tested each day, with testing only of newly symptomatic (divide by 7 day duration of illness) so as to not test the same person more than once in the same illness episode. We assume 50% of COVID-19 cases are symptomatic.
No TTI Lockdown Triggers – Targeted PTTI Face Coverings Lockdown Triggers –	**Lockdown and Lockdown Release Triggers.** As above five scenarios No TTI, Untargeted PTTI, Untargeted PTTI Face Coverings, Targeted PTTI, and Targeted PTTI Face Coverings , but instead of phased lockdown release, Lockdown released when <10,000 cases and Lockdown triggered when >40,000 cases.	Lockdown release is to *c* = c0 * 0.8 (80% of pre-pandemic contacts) after lockdown release.
Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	**Testing everyone but with lower success of tracing.** As Untargeted PTTI Face coverings Lockdown Triggers , though with lower success of tracing , eta (0%, 1 30%), at the same rate of tracing (chi=0.8). This is to contrast testing everyone (untargeted testing) with targeted testing of symptomatic people only – which needs higher levels of tracing to suppress the epidemic (≥40%).	
Untargeted PTTI 30% Tracing Success Face Coverings		

[1] The testing rate is calculated as follows. Let the base rate of testing in the population be θ_0. This must reflect all of those who are tested due to having symptoms, both from the cold or flu and from COVID-19. Let p_f be the prevalence of the cold and flu, t be the duration of symptoms, and k_t be the rate of testing. Therefore, the rate at which individuals are tested due to cold or flu symptoms is $\theta_0 = p_f k_t / t$. This rate impacts the costs: 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. [41,42]

Lockdown Triggers	
Untargeted to Targeted PTTI Face Coverings Lockdown Triggers	**Testing everyone but with switch to targeted testing and tracing after epidemic suppression.** As Untargeted PTTI 30% Tracing Success Face Soverings Lockdown Triggers but with two months of testing everyone every week to suppress the epidemic (from 31 August to 31 October 2020) then switching to targeted testing same as Targeted PTTI Face Coverings Lockdown Triggers from 1 November 2020
Targeted PTTI 30%/40%/50% Tracing Success Face Coverings Lockdown Triggers	**Targeted testing with lower tracing success.** As Targeted PTTI Face Coverings Lockdown Triggers though with lower success of tracing, eta (30%, 40%, 50%,), at the same rate of tracing (chi=0.8).

β (beta) = Transmission rate per contact

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

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 (0.3 is lockdown)

χ(chi) = Tracing rate per day

η(eta) = Proportion of people traced successfully traced and isolated

χ=0.8 and η=0.8, is interpreted as: 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, □□□(−□□□)giving the chance of being traced at time t. The cumulative distribution, *1* − □□□(−□□□), 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.

Economic model

We employ a cost–consequence analysis,[43] and methods consistent with an impact inventory,[44] to evaluate our 16 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.(Neumann et al. 2016; Walker et al. 2019) Instead, we allow decision-makers to make their own assessment of the success of each scenario based on the disagreggated 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 (Claxton et al. 2002). 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. Our findings are robust to these changes: though faster epidemics with shorter incubation periods and earlier transmission are more severe, they are not so severe as to alter our conclusions; even if masks are less effective than we think they are, they still help.

Results

Table 1 shows the results of all 16 scenarios. (Full results, including ICU cases, hospital cases, and non-hospital cases, are shown in supplementary Table S8, and supplementary material Tables S7–S10 compare scenario results.) All scenario trajectories are plotted in six-panel figures, with Targeted PTTI 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 seven key 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.

No TTI, which has phased lockdown release from June to August and no testing or tracing, results in an unmitigated epidemic with ~600,000 deaths and reduction in GDP of £496bn from the time already spent under lockdown. With lockdown triggers added (No TTI Lockdown Triggers), the deaths are reduced to around 112,000, with a £1,172bn (~£1.2 trillion) GDP loss. We used these two scenarios as the main counterfactuals against which to compare the PTTI strategies (supplementary material Table S6).

Given that physical distancing restrictions have been relaxed in the UK, the optimal strategy is Targeted PTTI Face Coverings Lockdown Triggers (i.e. targeted testing of symptomatic people only and tracing and isolation of the contacts of those who test positive, with a mandatory face coverings policy, and subsequent lockdown triggered to enable TTI to suppress the epidemic). This results in the fewest deaths (~60,000), and lowest intervention costs (~£12bn). The additional lockdown required reduces GDP by ~£537bn, about the same as No TTI without lockdown triggers, and about half as much as No TTI Lockdown Triggers (which also costs nearly twice as many lives).

With tracing success as low as 40%, targeted testing still suppresses the epidemic (Targeted PTTI 40% Tracing Success Face Coverings Lockdown Triggers, Figure 2, Table 1), though with ~23,000 more deaths (~83,000) and higher cases, leading to more time in lockdown (~£684bn reduction in GDP) and higher intervention costs (~26.5bn).

If feasible, testing everyone every week, combined with face coverings, could suppress the epidemic without tracing (Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers, Table 1). This is because, by capturing 80% of new infections each week, adding tracing does not significantly increase the speed of isolation of those who are newly infected. After this strategy has suppressed the epidemic, a strategy of targeted testing can be adopted in order to maintain epidemic suppression at lower intervention costs, provided there is contact tracing with success of at least 30% (Untargeted to Targeted PTTI Face Coverings Lockdown Triggers; ~74,000 deaths; ~£684bn reduction in GDP; ~£44bn intervention costs).

Targeted testing of symptomatic people would require testing up to 3.2% of the population every week in winter (80% of the estimated 4% of the population who have COVID-19 or cold or flu symptoms at their peak in winter[45]). This means testing ~300,000 people a day, up from the

estimated ~50,000 currently being tested.[46] Because the prevalence of cold, flu, and COVID-19 symptoms combined may be closer to 1% in June and July,[45] only ~75,000 people per day may need testing to start with under the targeted TTI strategies.

. Scaling up to test 80% of the population every week by 31 August while the lockdown is eased results in another epidemic wave that is then brought under control by TTI. A total of ~102,000 deaths occur under this scenario, which has total intervention costs of £182bn, of which £154bn are for tracing because of the large number of infections (Untargeted PTTI, Table 1). With lockdown triggers (Untargeted PTTI Lockdown Triggers) to prevent the epidemic from getting out of control, tracing requirements are manageable and the intervention averts an estimated ~53,000 deaths relative to no testing and tracing, also with lockdown triggers (No TTI Lockdown Triggers). Targeted PTTI is less effective than Untargeted PTTI without and with lockdown triggers (Table 1).

Adding mandatory face coverings reduces deaths:Untargeted PTTI Face Coverings: ~69,000 deaths compared to Untargeted PTTI: ~102,000 deaths; Targeted PTTI Face Coverings: ~99,000 deaths compared to Targeted PTTI: ~217,000 deaths) and saves intervention costs as less testing and tracing is required. With lockdown triggers, face coverings have more of an impact with targeted PTTI than untargeted PTTI (Table 1).

Targeted testing of symptomatic cases only and tracing, with face coverings, and lockdown triggers (Targeted PTTI Face Coverings Lockdown Triggers) can be as effective as weekly untargeted testing of everyone under the same conditions (Untargeted PTTI Face Coverings Lockdown Triggers; Table 1).

When testing is scaled up to testing everyone every week from 31 August 2020, total testing costs by 31 May 2022 are ~£28bn (Untargeted PTTI scenarios, Table 1 middle section). Tracing costs for these scenarios are similar, though higher r when the epidemic is not suppressed and runs out of control (see trajectories in supplementary material
With testing of symptomatic people only, testing costs are contained to around ~£700m (Targeted PTTI scenarios, Table 1 bottom section). Tracing costs are very high when the targeted testing and tracing is unable to keep the epidemic suppressed (Targeted PTTI: ~£90bn, ~217,000 deaths). They are much lower when the epidemic is suppressed (Targeted PTTI Face Coverings Lockdown Triggers: ~£12bn, ~60,000 deaths, Table 1). The latter scenario involves subsequent triggering of lockdown to control the epidemic when active infections increase to greater than 40,000.. These results highlight the trade-offs between additional lockdown, and targeted and untargeted testing. Further details can be found in the supplementary material.

The results of our sensitivity analyses are shown in supplementary material Tables S11-S19and supplementary Figures S17-S24 In the base case, with a 25% reduction in GDP under lockdown, No TTI Lockdown Triggers causes a £635bn 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 £254bn and £1.0 trillion, respectively. Varying the effectiveness of face coverings to 5% (from 15% base case) results in the Face Coverings scenarios being less able to suppress the epidemic, so that results are closer to those without face coverings (Table S15, Figure S19). When face coverings are assumed to be 30% effective, Face Coverings scenarios suppress the epidemic more easily, which also reduces GDP loss. (Table S16, Figure S20). 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 and more time under lockdown (Table S17, Figure S21). If the proportion of cases that are symptomatic were 80%, targeted testing would suppress the epidemic more easily, with lower mortality and less time under lockdown (Table S18, Figure S22). If the infectious period is 5 days (base case 7 days) PTTI is less able to suppress the epidemic and there are 20-100% more deaths in each scenario (Table S19, Figure S23). If the incubation period (base case 5 days) is shortened to a 3 day latent period there are 5-50% more deaths in each scenario (Table S20, Figure S24).

Table 1 Scenario results

To 31 May 2022	No TTI	No TTI Lockdown Triggers	Key:	Lockdown triggers	face coverings	*targeted testing (symptomatics only)*
Deaths	**661,156**	111,766				
NHS costs (£bn)	**4.8**	0.8				
reduction in GDP (£bn)	**495.9**	1,172.2				
Public Health costs (£bn)	**0.0**	0.0	**lower success of tracing , eta (00=0%, 10=10%, 20=20%, 30=30%, 40=40%, 50=50%, 60=60%, 70=70%, default is 80%)**			
of which: Testing total costs (£bn)	*0.0*	0.0				
Tracing total costs (£bn)	*0.0*	0.0				

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Deaths	**102,495**	**58,405**	**69,360**	61,514	75,131	**59,179**	**74,262**
NHS costs (£bn)	**1**	**0.4**	**0.5**	0.5	0.6	**0.4**	**0.5**
reduction in GDP (£bn)	**495.9**	**553.5**	495.9	521.4	**588.9**	**553.1**	683.7
Public Health costs (£bn)	**181.8**	**48.7**	91.2	58.2	**75.4**	**64.6**	43.9
of which: Testing total costs (£bn)	***27.9***	**28.2**	28.1	28.1	**28.2**	**28.2**	4.3
Tracing total costs (£bn)	***153.9***	**20.5**	63.1	30.0	**47.2**	**36.4**	39.6

	Targeted PTTI	Targeted PTTI Lockdown Triggers	Targeted PTTI Face Coverings	Targeted PTTI Face Coverings Lockdown Triggers	Targeted PTTI 30% Tracing Success Face Coverings Lockdown	Targeted PTTI 40% Tracing Success Face Coverings Lockdown Triggers	Targeted PTTI 50% Tracing Success Face Coverings Lockdown Triggers

				Triggers			
Deaths	**216,517**	**86,121**	**99,119**	60,334	94,763	**82,956**	**76,005**
NHS costs (£bn)	**1.6**	**0.6**	**0.7**	0.4	0.7	**0.6**	**0.6**
reduction in GDP (£bn)	**502.8**	**673.7**	**495.9**	537.3	704.5	**684.4**	**630.8**
Public Health costs (£bn)	**91.0**	**26.0**	**23.2**	12.4	33.0	**26.5**	**21.1**
of which: Testing total costs (£bn)	*0.7*	**0.7**	**0.7**	0.7	0.7	**0.7**	**0.7**
Tracing total costs (£bn)	*90.3*	**25.3**	**22.5**	11.7	32.3	**25.8**	**20.4**

Figure 1: Trajectories for Targeted PTTI Face Coverings Lockdown Triggers . Scale-up to 80% of symptomatic people tested with 80% of contacts traced and 80% successfully isolated by 31 August, Face Coverings policy from 4 July, additional Lockdown triggered when cases rise above 40,000 and released when cases fall below 10,000. 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.

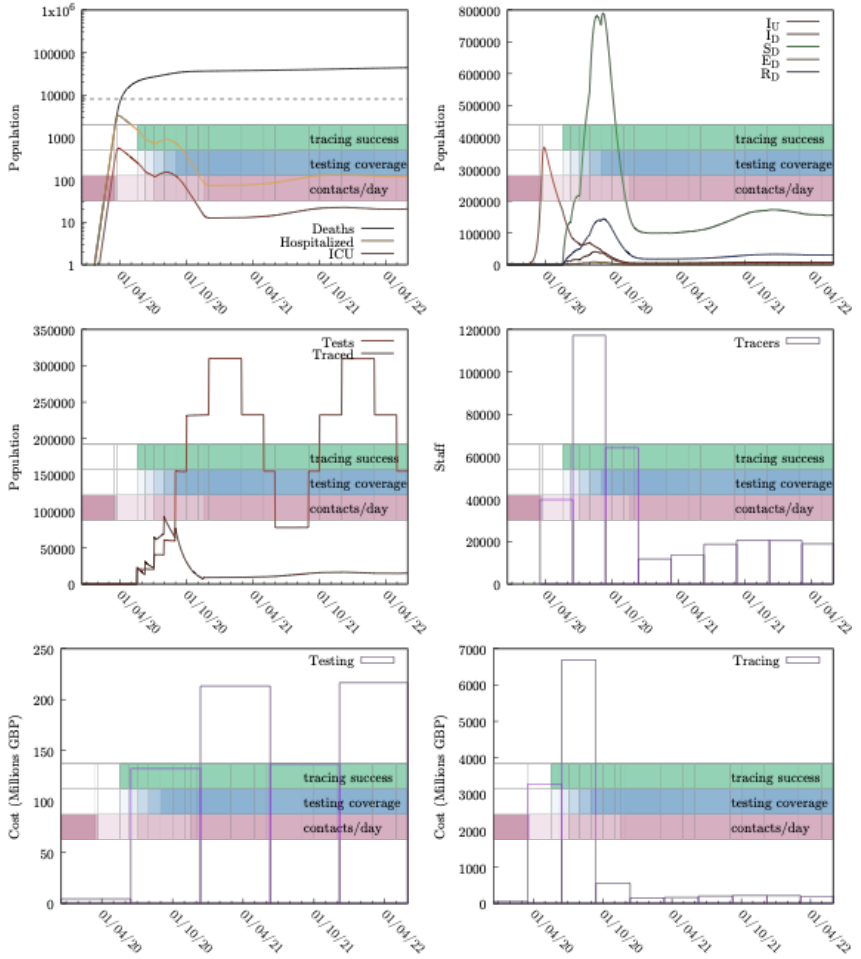
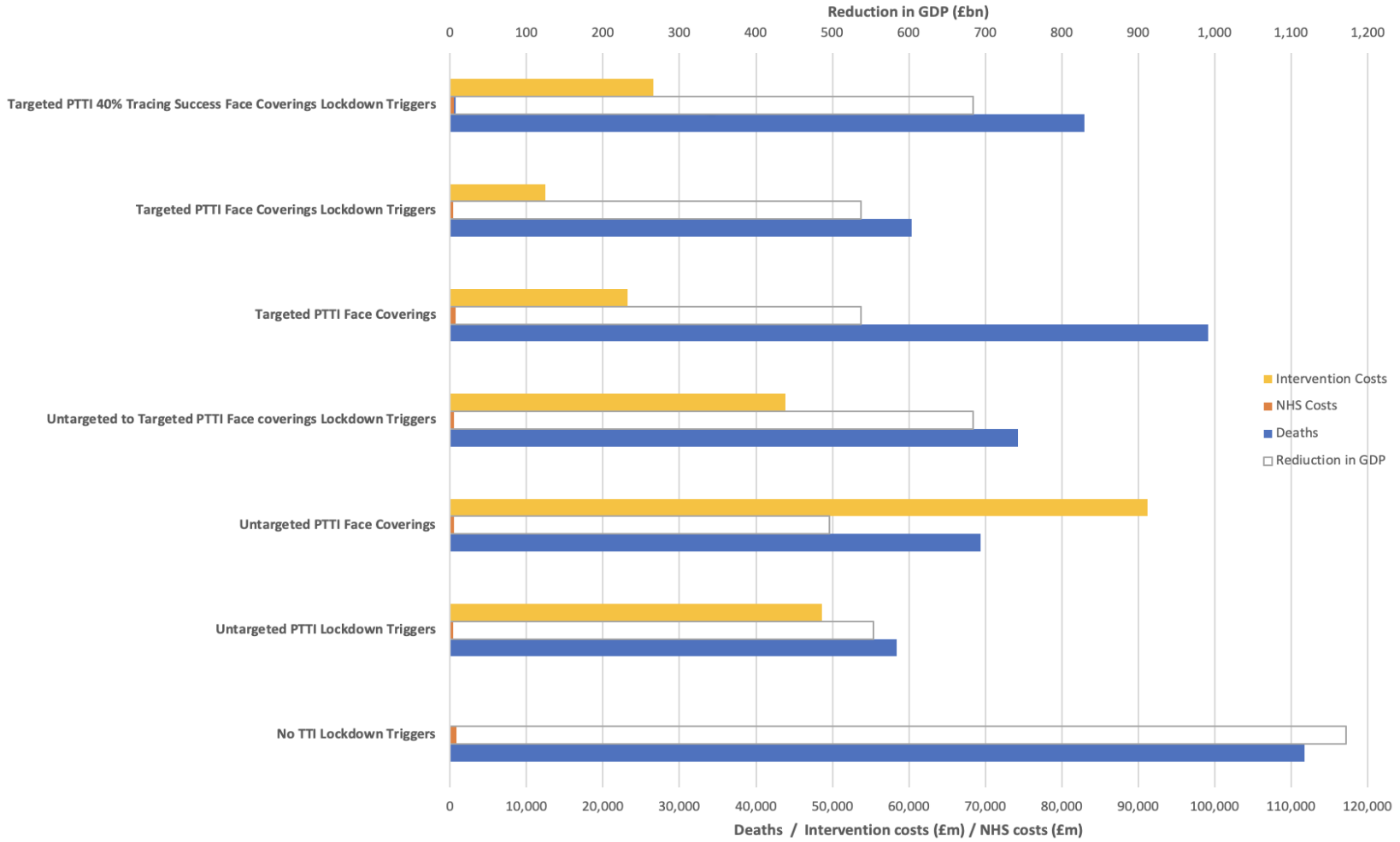


Figure 2 **Health and Economic outcomes of selected Population-scale Testing, contact Tracing and Isolation (PTTI) strategies to control the COVID-19 epidemic in the UK – scenarios run to 31 May 2022.**



Discussion

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

The analysis suggests the best option is nationwide testing of symptomatic individuals and isolation of cases and their contacts, combined with mandatory face coverings in public spaces. The release of lockdown should be delayed, or implemented very gradually, as this system is scaled up. 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 (as of 27 June 2020, number of people not shown33 so hard to estimate[46]). Of the modelled scenarios, this would result in the fewest COVID-19 deaths (~60,000), the lowest intervention costs (~£12bn), and £537bn reduction in GDP by 31 May 2022, including the costs already incurred due to lockdown and the pandemic. Without PTTI, we estimate that 112,000 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 300,000 per day in winter when there is a higher prevalence of cold and flu symptoms, which can be confused with COVID-19. Assuming 50% of COVID-19 infections are symptomatic, targeted testing of symptomatic people with 80% coverage should diagnose 40% of all COVID-19 infections. The epidemic can still be suppressed due to amplification of the effect of testing by tracing and isolation, i.e. assuming 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.

While untargeted 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. Untargeted testing of everyone every week, if it were feasible, may work without tracing, at a higher cost (Untargeted PTTI 0% Tracing Success). This cost could be reduced by switching to targeted testing after the epidemic is suppressed (Untargeted to Targeted PTTI), though we note the epidemic could be similarly suppressed with targeted testing itself even when tracing and isolation has a 40% success rate (*chi* 0.8, *eta* 0.5, Targeted PTTI 50% Tracing Success Face Coverings Lockdown Triggers, Table 1). This 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.[47]

We note that, while we have looked at a variety of scenarios with variations in testing and tracing, we have not exhausted all possibilities. Testing and contact tracing individually have different scaling properties and can be mixed in different proportions. Testing alone scales linearly with the population: a population twice the size requires twice the number of tests. It is therefore possible to suppress the virus with a strategy that tests everyone without tracing (Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers, Table 1, Figure S7).

But to effectively suppress an outbreak using only testing, it has to be done sufficiently frequently and in a sufficiently large proportion of the population to be confident of identifying a very high proportion of infectious individuals. Because tracing follows the path of the outbreak itself through the population, the cost of tracing increases exponentially with the number of infections. When prevalence is high, it is theoretically more efficient and less costly to simply test the entire population. However, the infrastructure in the UK could not deliver this in the necessary timeframe. When prevalence is low, a far smaller number of tests is needed, and rapid contact tracing becomes feasible and less burdensome. Thus, the best strategy, whether frequent testing or combining scaled testing and tracing, depends on the prevalence within the population. Our study gives insight into this and aims to inform the policy decision makers.

The combination of economic, policy, and epidemiological concerns is critical and our work is the first to shed light on all three. Firstly, our analysis, unlike others to date,[48,47,49–51 52] 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 as we move forward out of the lockdown.[53] Our study is the first to evaluate the costs of different exit strategies, giving feasible options that can both save lives and protect the economy.

Secondly, we modelled testing, tracing, and isolation strategies in a novel way. Previous approaches have either been too simple to accurately capture both the epidemiological and economic effects of TTI or too complex for rapid and flexible exploration of policy options. The simple approach which asserts that TTI modulates the rate of disease transmission[48] or isolates a proportion of exposed individuals[47,49–51] does not adequately capture the dynamics of contact tracing.[25] An alternative is detailed individual-based models (IBMs) tracking the transmission of individuals,[52] and existing detailed IBMs come to broadly similar conclusions.[54] 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[54] suggest that TTI should focus on scaling targeted symptomatic infection, with sufficient tracing and isolation of symptomatic and diagnosed positive individuals. Kucharski and colleagues suggest that for a large outbreak, suppression requires a significant reduction in contact rate for tracing to work.

Finally, our approach generates actionable policy insights.[55] Some recent analyses of policies do not model contact tracing as an option,[56–58] leading to conclusions about tradeoffs between a non-exhaustive set of options. Others do model contact tracing as a policy option, but use a simplistic representation of contact tracing,[59] which does not allow consideration of the policy choices faced by decision makers. On the other hand, epidemiological studies that model tracing in enough depth to properly represent its dynamics and policy options find that it would be effective, but do so without without considering the economic impacts,[47,50,60–62] making it difficult to assess the actual policy tradeoffs involved in more or less restrictive versions of the policy. It is important to note that PTTI could be abandoned when drugs or a vaccine become available without 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 but found PTTI was less able to suppress the epidemic and there were 20-100% more deaths in each scenario (Table S19, Figure S23).

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,[63] 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 (5.4% in June 2020 according to seroprevalence data for the UK[64]), and relatedly, the infection fatality rate. These parameters remain uncertain though we use what we believe are the best currently available estimates.[4,6,65] We focus on mortality, though chronic illness and organ damage from COVID-19[66] 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.[62] As noted above, the contact tracing success rate could be far lower than modelled, but unless compliance is less than half, corresponding to a success rate of 40% rather than 80%, these strategies can still be effective, albeit less so. Policies to support effective isolation, such as community support and volunteers to run errands for those isolated, are therefore potentially important. 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 may be optimistic, but the need to enforce compliance is true of any infection control system, and is expected to have minimal impact on the relative value of the approaches – which still are far more effective than allowing uncontained spread.

A general point should be made about this class of model, independent of calibration or fitting of any particular parameter values. This is a well-mixed model, meaning that each non-isolated individual has an equal chance of encountering any other non-isolated individual. The effect of this structural assumption is that such models will tend to overestimate the spread of the disease. Real populations have more structure which means that the pool of susceptible individuals in a local contact network can become exhausted and retard the propagation of the virus through the population as a whole. We do not, however, have data to ascertain the magnitude of this effect.

Simultaneously, the chance of a contact being traced is assumed to be proportional to having had at at least one infectious contact. An alternative formulation could be that the chance is proportional to the *number of* such contacts, which of course would mean that tracing should happen faster. Both of these structural assumptions act to systematically overestimate the severity of the epidemic and underestimate the effectiveness of contact tracing. As such, they err on the side of safety. If we construct a PTTI regime aiming to achieve the recommendations that we give here, we have some margin for error in the not-unlikely event that we fall short.

All mathematical and computational models are simplifications and the one underlying this analysis is no different. Several relevant phenomena are only captured indirectly and could usefully be explicitly included in a more sophisticated model. The relevant distinction between asymptomatic and symptomatic individuals for the purposes of outbreak control is equivalent in this model to a reduction in the proportion of the population that is tested, in the cases where targeted testing is considered. Similarly for imperfect isolation: this is captured with a lower testing and/or tracing rate as no distinction is made between not isolating someone and isolating them and having them not comply. There is an asymmetry here, however, in that the economic impact of imperfect isolation is not accounted for. A lower rate of isolation not only means a lower rate for infectious individuals but also lower for those susceptible or recovered individuals erroneously isolated. We suspect that this effect will be relatively small but confirmatory research is needed. Finally, 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[67], and that self- collected saliva samples compare favourably with nasopharyngeal or oropharyngeal swabs[68]). There is a trade-off between having a model that is rich enough to provide useful insights into which strategies for outbreak suppression are likely to work and having one that is so detailed that it is difficult to understand the underlying interactions and dynamics. We have deliberately chosen a simple model to understand the interaction between, and relative merits of, testing and contact tracing, and the economic implications of these strategies both individually and in combination.

Other significant uncertainties are the effects of lockdown on the UK economy and the costs of testing. For the effects of lockdown on GDP we assume GDP reduction scales with lockdown (c contacts per day) so is directly related to the time spent under lockdown, which in turn is related to the scenarios we consider, including the scenarios where subsequent lockdowns are triggered when active cases go above 40,000. 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. Although a more detailed economic model would be ideal, the available economic evidence is very limited. As with any economic model, we must consider a balance between how well the model represents reality and the quality of the available evidence to populate the model. The costs of testing are converging around our estimate given new methodologies that can be applied at scale.[69] Importantly, our conclusions regarding the need for targeted PTTI 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.[70] 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

Mathematical model

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

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

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

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

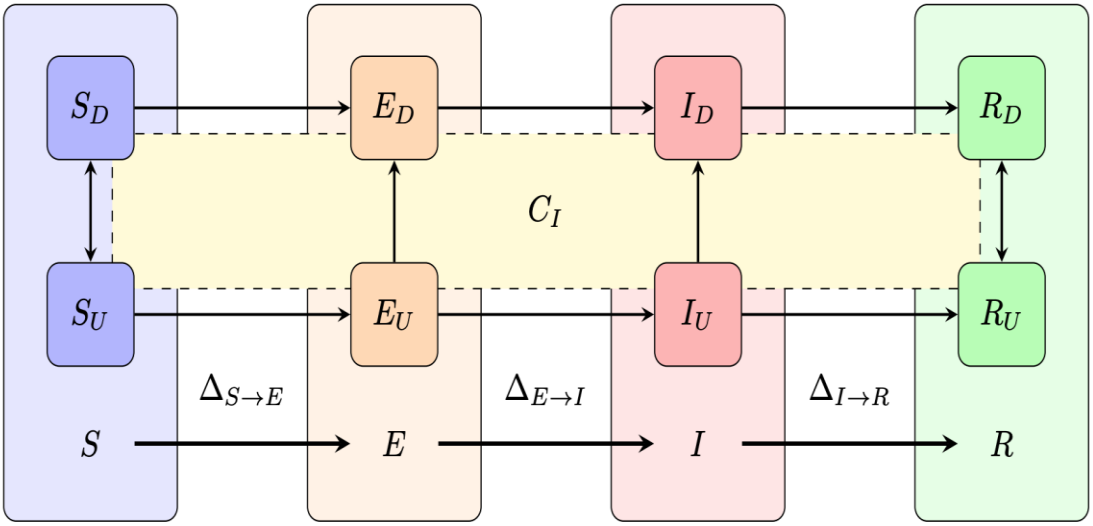


Figure S1 Schematic of an SEIR model with diagnosis described by testing and contact-tracing. SEIR is a compartmentalised model describing susceptible (S), exposed (E – infected but not infectious), infectious (I) and removed (R) population cohorts. Individuals move between these compartments in sequence 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[25] and is shown schematically in Figure S1. The model was parameterised using existing literature. Parameters used for the purposes of this analysis are shown in Table S1. Specifically, we use estimates of exposure time of 5 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 BBCPandemic social mixing study for the UK,[71] which aligns with earlier UK data on social contacts.[72] 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,[73] which we assume applies for the duration of

the lockdown. For the relaxation of lockdown we use an estimate of *c* increasing to 40% of baseline from 9th June (week of 5th-12th June 2020,[74] then assume *c* increases to 60% of baseline from 4th July when entertainment venues are due to open and physical distancing restrictions relaxed, rising to 70% of baseline on 31st July and 80% of baseline on 31st August as people mix more in response to the new policy. We assume no further increases in contacts per day throughout the next 2 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,[364] while deaths were estimated at 41,000,[75] implying an IFR of 1.1% (0.9%, 1.4%). Deaths may have been as high as 60,000,[76–78] 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 [79], 18 days after lockdown on 23 March. Moreoever, 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[80] (Figure E4 in the data supplement of the paper[80]). 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	[81]
c	Average contacts per day	11	[71]
β (beta)	Transmission rate per contact	0.0425	Estimated from fit to mortality data[75]
α^{-1} (alpha)	Incubation period (time from exposed to infectious)	5 days†	[82–85]
γ^{-1} (gamma)	Recovery period (time from infection to recovery or hospitalisation)	7 days†	[86,87]
κ^{-1} (kappa)	Isolation period (symptom free days)	14 days	[88]
θ (theta)	Testing rate of infectious individuals	0	-
χ (chi)	Contact tracing rate	0	-
η (eta)	Efficiency or success rate of contact tracing	0	-

* values used in modelled scenarios shown in Panel 1

† values from the literature come with wide confidence intervals

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(Medical Masks vs N95 Respirators for ...), the only two completed clinical studies of masks in COVID-19 are observational. In a non-peer-reviewed pre-print, Doung-ngern and colleagues(Doung-ngern et al. 2020) report a large protective effect of wearing a mask "all the time" (adjusted odds ratio [OR] 0.23 [0.09–0.60]), but not "sometimes", among contacts of cases in Thailand. Wang and colleagues[89] find similar benefit (OR 0.21 [0.06–0.79]) in China within households. In addition, two recent systematic reviews with meta-analyses have examined mask usage in related viruses. Chu and colleagues(Chu et al. 2020) report a 44% benefit (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-1 pandemic. Similarly, in an analysis that included studies of A(H1N1)pdm09 and influenza as well as SARS, Liang and colleagues(Liang et al. 2020) 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, in 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.[34–36] 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[34,90]). Second, masks have been shown to reduce emission of various pathogens, including influenza viruses and Mycobacterium tuberculosis, in experimental conditions.[91,92] Third, there is some evidence that SARS-CoV-2 is more reliant than other pathogens on relatively large droplets for transmission,[93–95] and masks are better able to filter out droplets than small particles. This may help explain the larger protective effect(Liang et al. 2020) in SARS (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. This 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.[34] 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% (40–90%).

On the other hand, the face coverings used in relevant studies are typically medical masks, or made of unspecified material. A recent survey[96] 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.[33] 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[97] – although the difference is likely to be smaller for coronaviruses.[35] When including studies in a healthcare setting, Chu et al.'s review[30] 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[37] of data from Chu et al.,[30] Liang et al.,[31] and Wang et al.,[89] 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.[27,35,98] 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 35% (15–60%) 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 a YouGov/Imperial survey on 5 June, just 21% of the British public reported always wearing a mask outside, compared to over 60% in some other Western countries without legal mandates.[38] However, the same survey suggests over 80% compliance in countries with such laws in place, and Transport for London claims over 90% usage on trains and buses,[39] where masks have been compulsory (and offered free of charge) since 15 June. Other surveys suggest lower figures across the board.[37] 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).

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.[2] Briefly, we match the number of model projected deaths to the reported UK deaths associated with COVID-19, using an infection fatality rate (IFR) of 1.0% 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 0.042 (which translates to a basic reproduction number [R_0] of 3.2 when c is 11 contacts per day when there are no interventions). We note that while we have taken 18th December 2019 as the date for the onset of the epidemic in the UK, as a modelling assumption, it is possible to also fit the initial epidemic with other dates. In fact, the fit to the data is not strongly sensitive to the onset date largely because the greatest weight of the data is for the lockdown period where R is near to 1 and the data from before that time is of poor quality.

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 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 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

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

recent review identifies studies estimating the true proportion could be between 43% and 98% (asymptomatic proportion: 2% to 57%[99]). 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 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[100] – 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[80] and 36.3% of non-ICU hospitalised cases die due to COVID-19.[80] 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,[101,102] factoring a mean of three organs supported;[103] and £346 per day for non-ICU cases.[104] 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.[80] 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,[105] 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[106] 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 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
Online training for all staff		1	Three training courses (including refreshers) one for each staff cadre. Assume repeated every 3 months		
				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[7]	£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.[69]

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[107]

Sector			Processes affected	Potential adverse health outcome
NHS	Programmes	Screening across the lifecourse, e.g. neonatal, cancer	Delivery, uptake and action[108]	Avoidable morbidity and mortality
		Immunisation	Reduced uptake[109]	Reduced herd immunity Increase in vaccine preventable infection
	Child and adolescent health		Health visitor checks and support for parents Adolescent mental health[110] 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[111]	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[112]
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[113] Disrupted support services during lockdown Removal of temporary housing at the end of COVID-19	Poorer health outcomes
	Dementia	Isolation, less carer support[114] Harms e.g. falls	Poorer quality of life Higher morbidity and mortality
	Patients with disability	Access to services for complex medical needs[115] Isolation Anxiety – may not be a 'priority' group for ICU Inequity in access to public health messaging	Worse health outcomes
	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[116]	

		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[117] 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[118] 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[119] Increased rates of depression[119] Increased rates of condition related anxiety (COVID patients)[119]	Difficulties accessing primary care for early diagnosis and treatment	Avoidable morbidity and mortality
Social isolation and distancing measures	Household isolation		Less physical activity Mental health (stress, insomnia, anxiety, depression) Domestic abuse Family breakdown Elder abuse Safeguarding Loneliness Infection transmission from crowding Increased substance misuse Poorer diet (BMI impact, type 2 diabetes risk) Reduced access to medications Increased experiences of racialised policing (BME groups) Loss of access to public spaces (closure of parks likely to impact communities who live in crowded housing) Lack of access to free school meals for children who need them, and increased use of food banks	Depression Suicide Physical trauma Adverse impact on physical WB Increased falls in the elderly isolated at home Poor reporting of moderate health risks to health professionals (i.e. early signs of cancer, heart disease, etc)
	Access to food	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[117]				

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.[120] Nevertheless, personal follow-up on foot will also be required to ensure all contacts, including the most vulnerable, are reached.[121] 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.[122,123] 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.[124]

Case finding and contact tracing
Contact tracing remains a key control measure for maintaining suppression of case counts.[125] Table S5 shows the staff needed to handle new cases and control spread through contact tracing and isolation.[126] 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[127] and R_0 of 2.5[128])	

***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.[129]
†**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.[129]

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)														
30th April	194,720	45,991	89,757	1,759,526	117,945	272,608	200,654	140,198	191,011	178,030	175,804	259,997	132,410	2,089,994
31st May	39,545	9,340	18,228	357,336	23,953	55,363	40,750	28,472	38,792	36,155	35,703	52,802	26,891	424,449
30th June	6,361	1,502	2,932	57,481	3,853	8,906	6,555	4,580	6,240	5,816	5,743	8,494	4,326	68,277

Number of contact tracers required for each new case to be traced in one day (7.5 hours work per contact tracer per day) on 31st May	5,273	1,245	2,430	47,645	3,194	7,382	5,433	3,796	5,172	4,821	4,760	7,040	3,585	56,593
Number of contact tracers required for each new case to be traced in one day (7.5 hours work per contact tracer per day) on 30th June	848	200	391	7,664	514	1,187	874	611	832	775	766	1,133	577	9,104
Contact tracers per case	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1

*Note: 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[126] (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[130] 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.[131] Most local authorities have established volunteer registers[132] 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.[133] 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,[134,135] which has been affirmed by evidence from previous epidemics including HIV[136,137] and Ebola.[138] Community-led and co-production approaches in the context of the COVID-19 response have been lacking,[139] 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.[140] 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[141,142] and can have positive knock on effects for mental health outcomes in the general population, which is a growing concern in the crisis.[143]

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

1. A register of names, dates of birth, and addresses of all residents registered with a GP, to be updated as necessary with test results, changes of address and addition of unregistered subjects. Anonymous registration with local outlets for sample collection and delivery is needed for those reluctant to give name and address. "Ghost patients"[144] can be dealt with using the strategy developed by the ONS.

2. New 96-well machines running direct RT LAMP assays[145] 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,[69] 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.[9,10] The UK government's five-pillar plan for scaling up COVID-19 testing[146] reaches out to local manufacturers to ramp up testing capability and pharmaceutical companies are also offering to help.[147] 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.[148] 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[149] (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.[150] 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.[150]

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[151]).

Supplementary Results - Scenario trajectories

Figure S1 No TTI trajectory

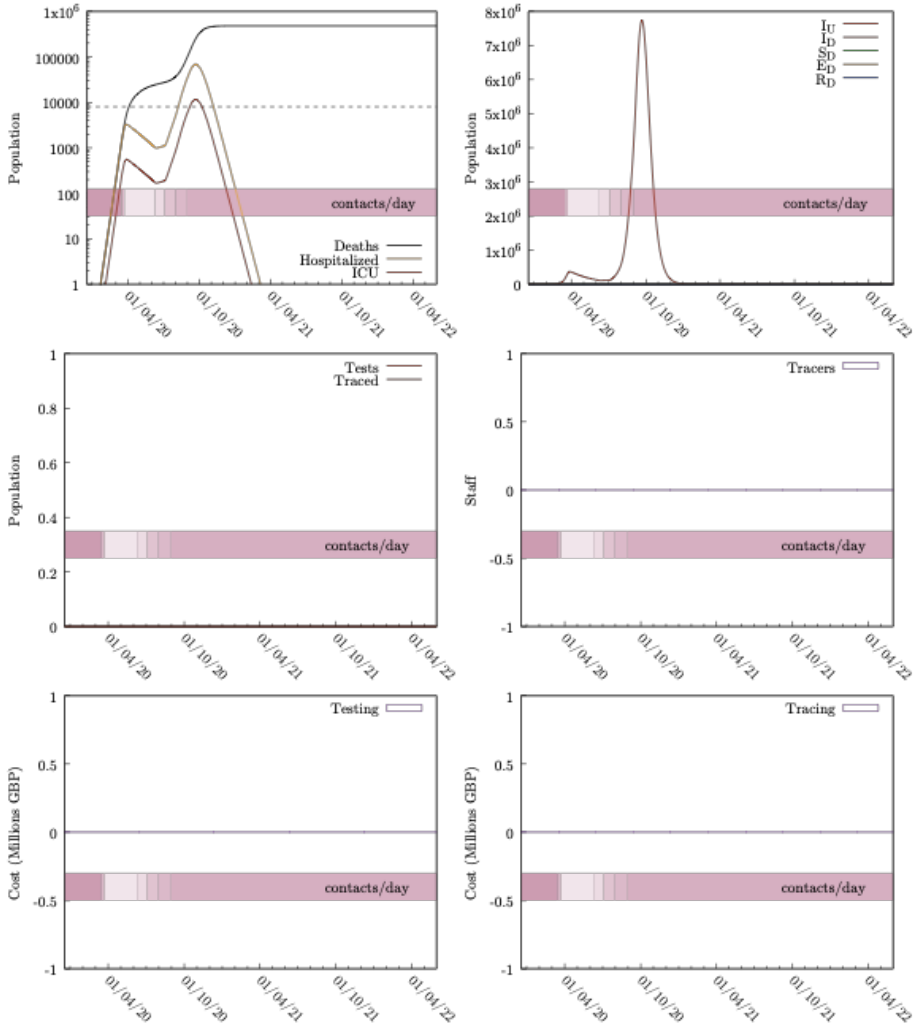


Figure S2 No TTI Lockdown Triggers trajectory

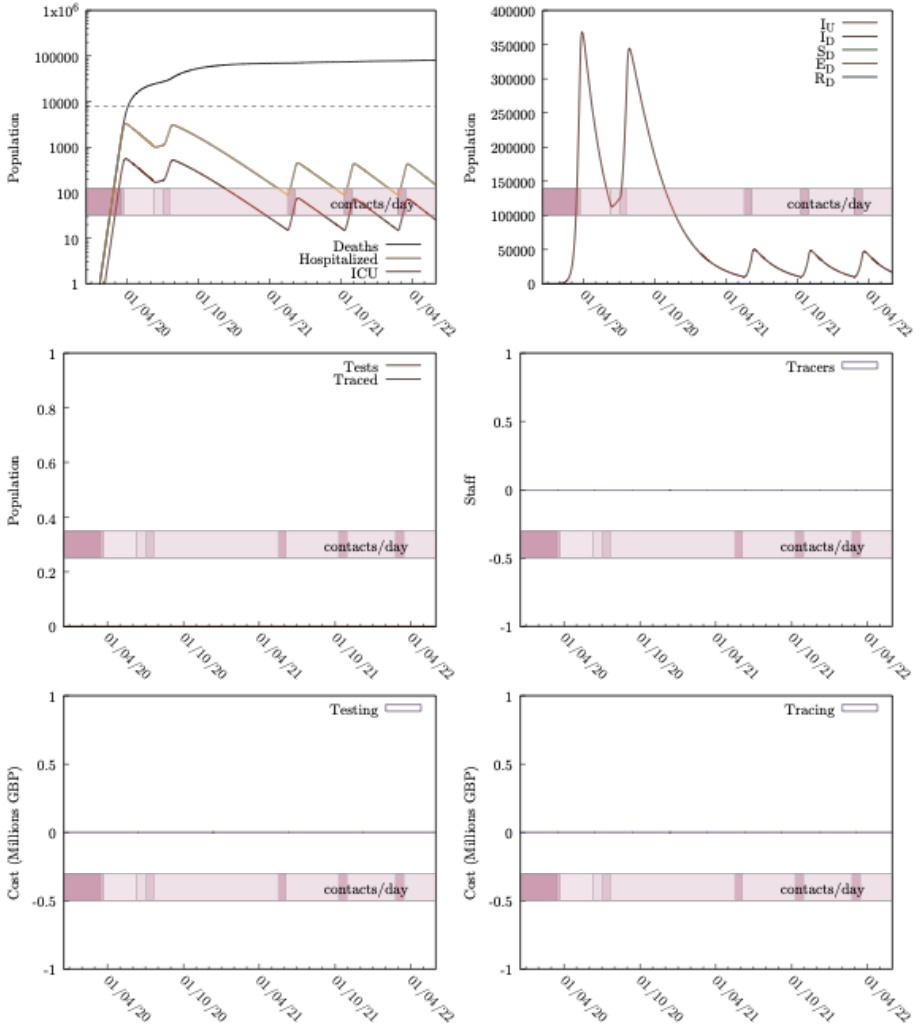


Figure S3 Untargeted PTTI trajectory

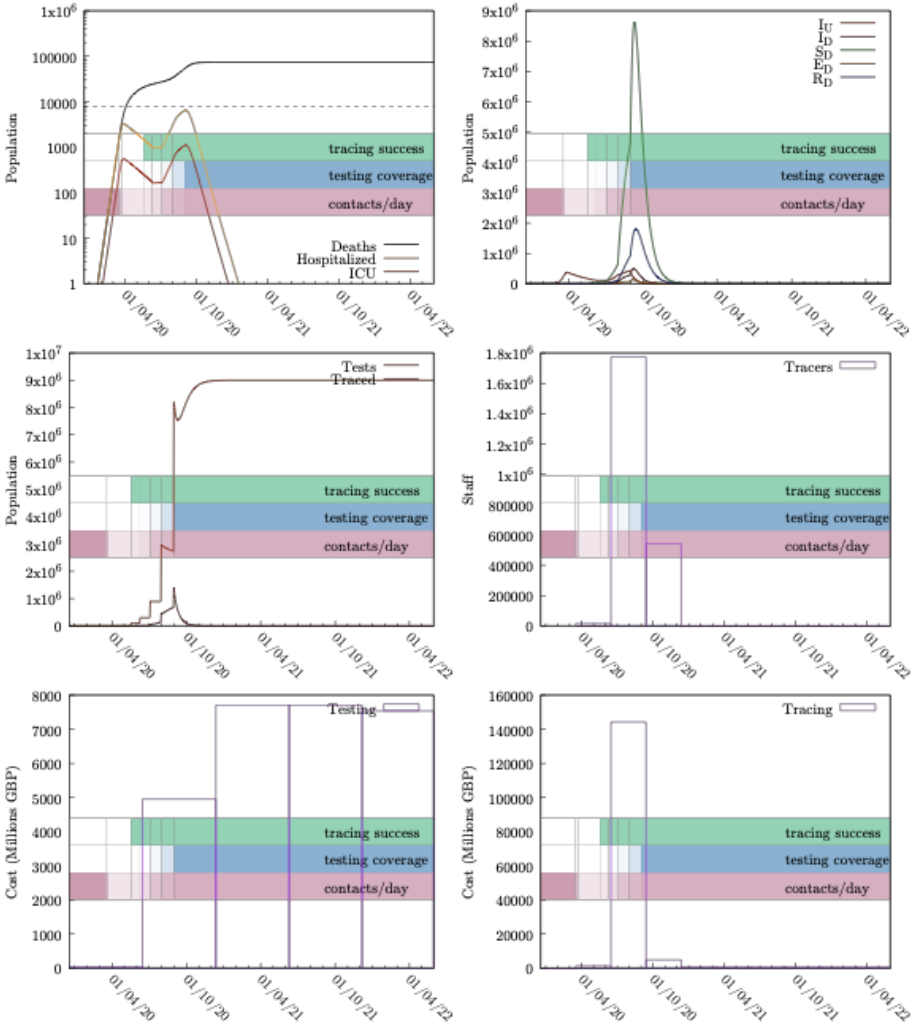


Figure S4 Untargeted PTTI Lockdown Triggers trajectory

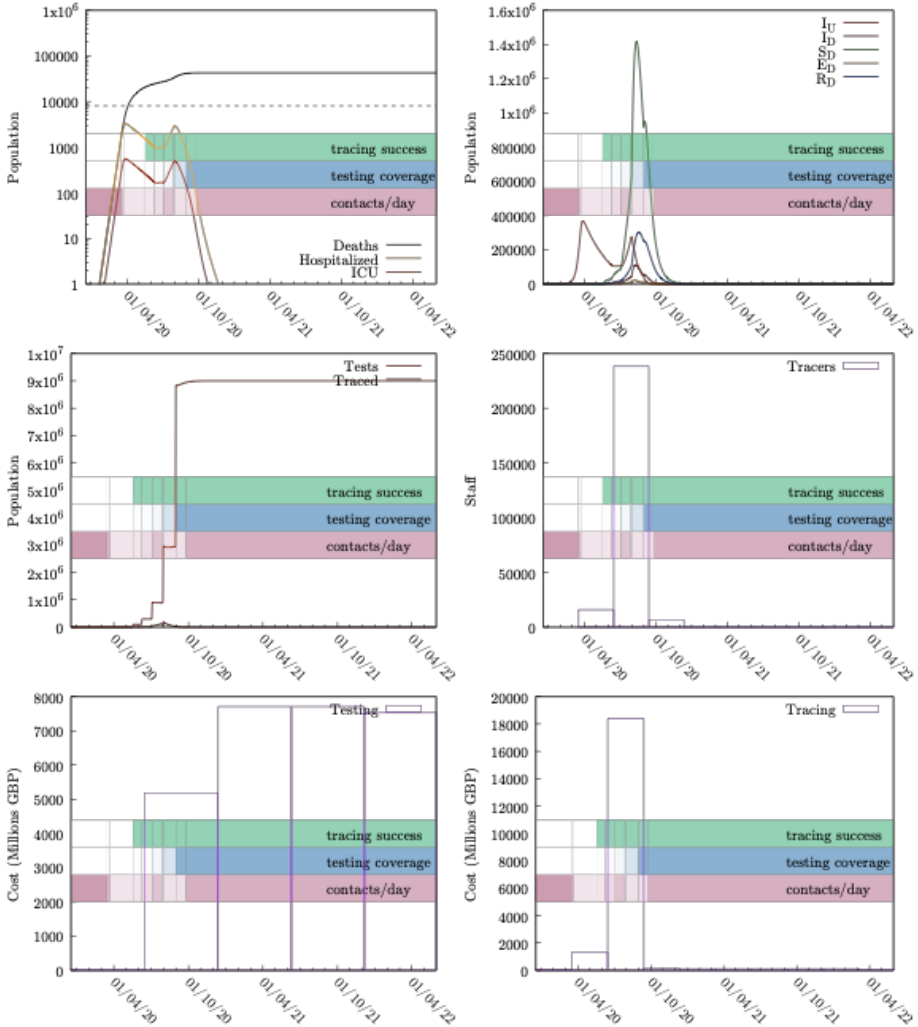


Figure S5 Untargeted PTTI Face Coverings trajectory

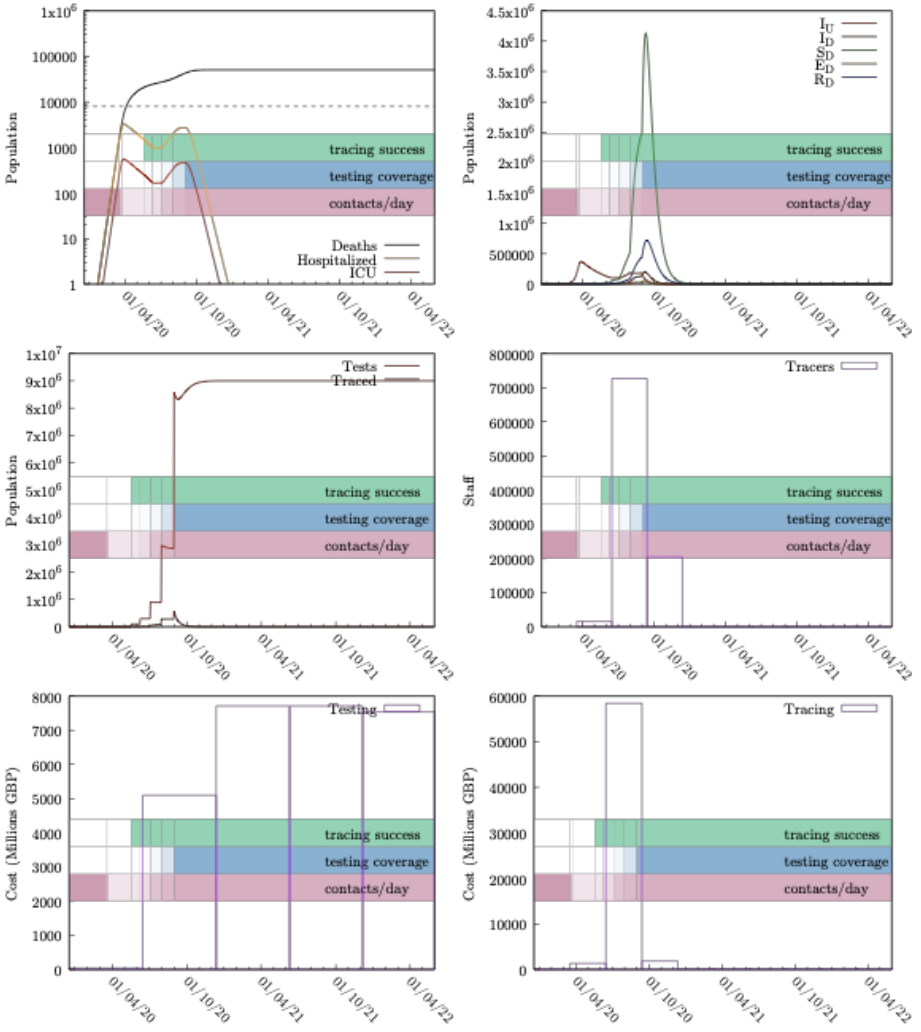


Figure S6 Untargeted PTTI Face Coverings Lockdown Triggers trajectory

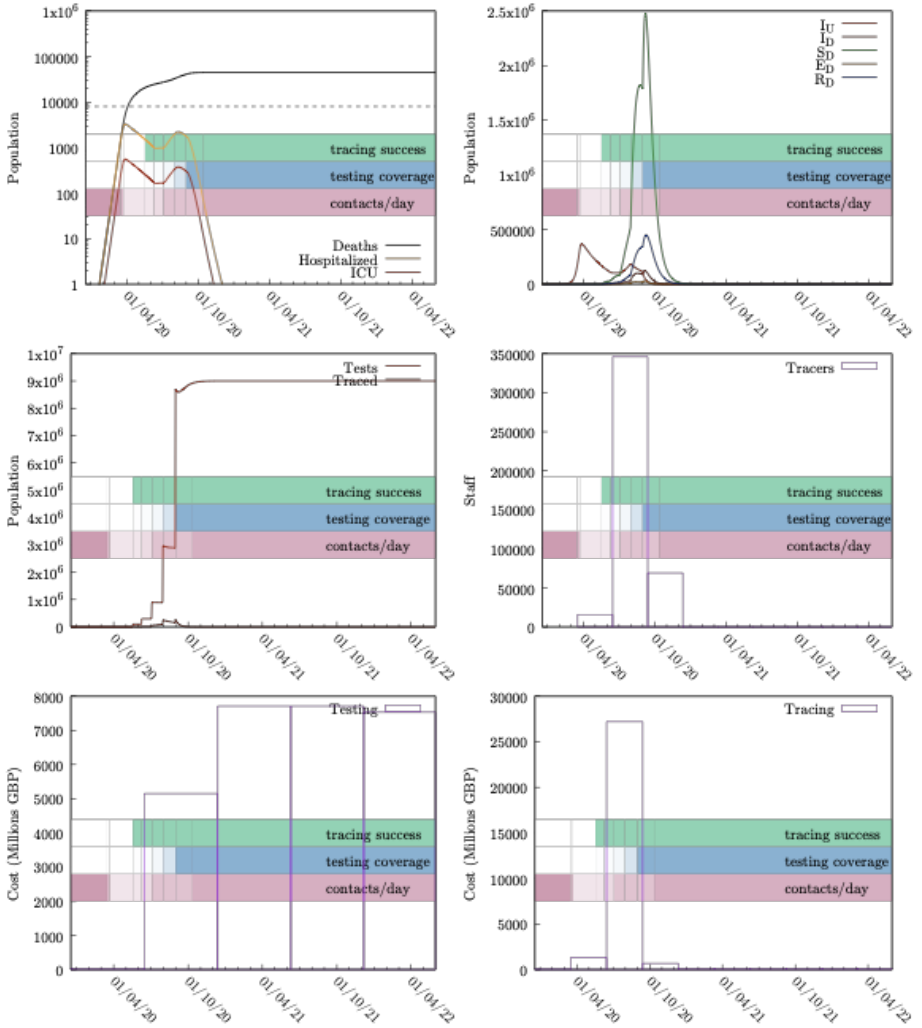


Figure S7 Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers trajectory

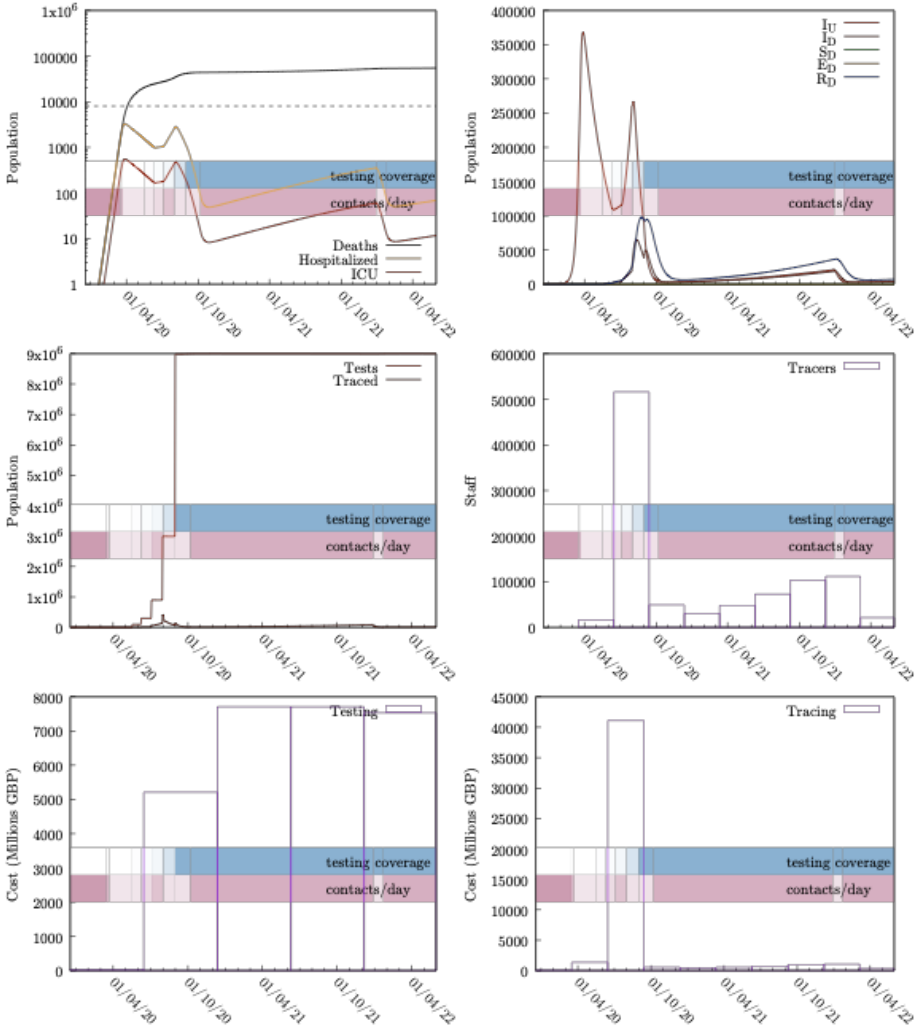


Figure S8 Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers trajectory

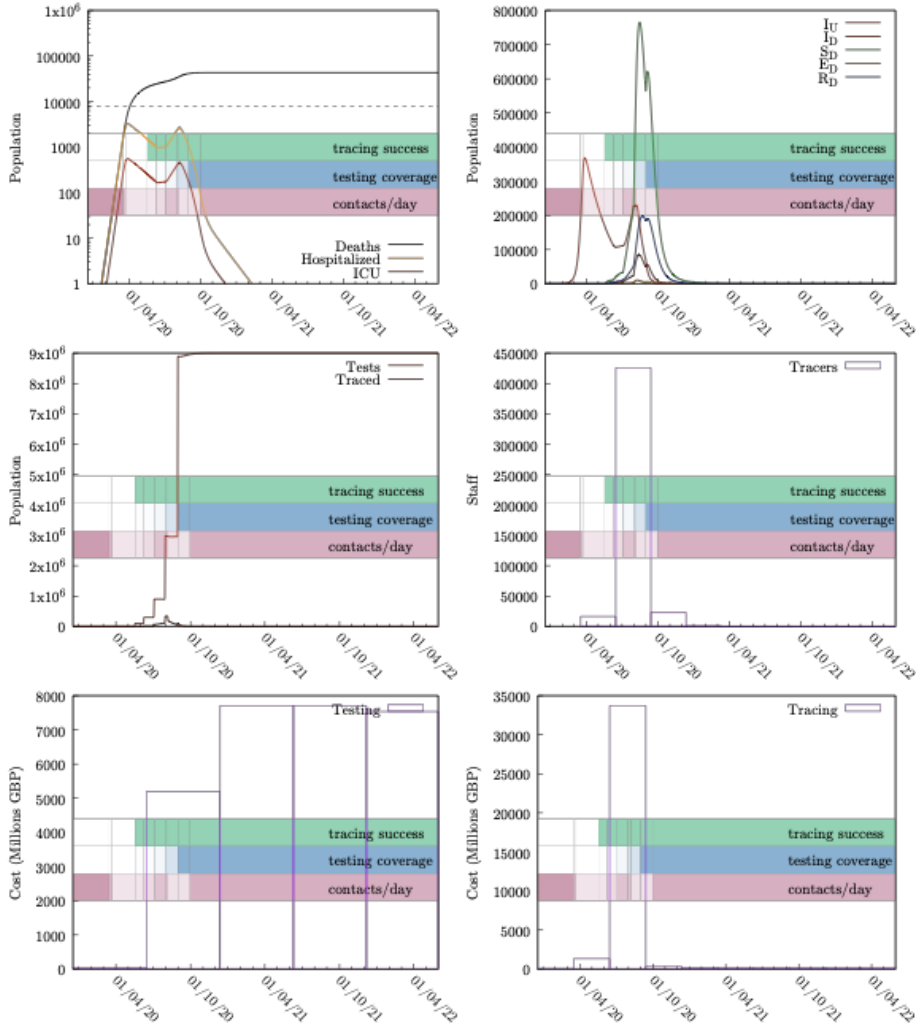


Figure S9 Untargeted to Targeted PTTI Face coverings Lockdown Triggers trajectory

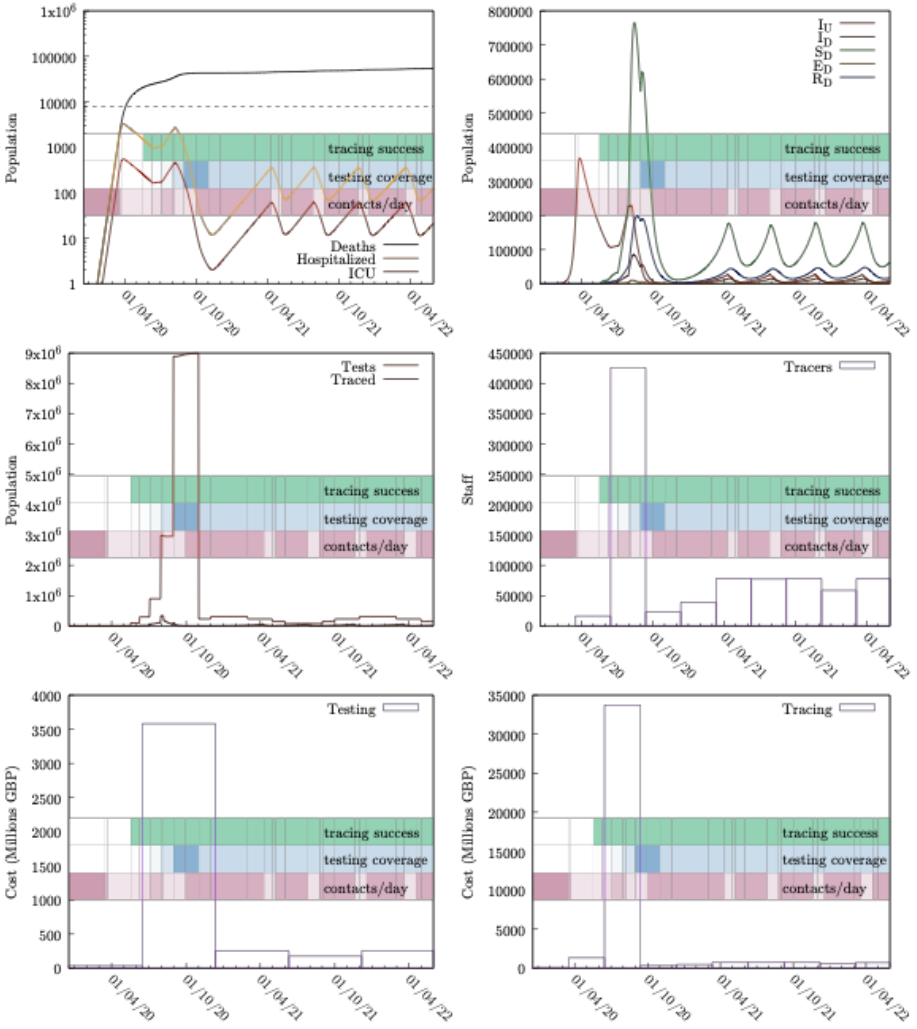


Figure S10 Targeted PTTI trajectory

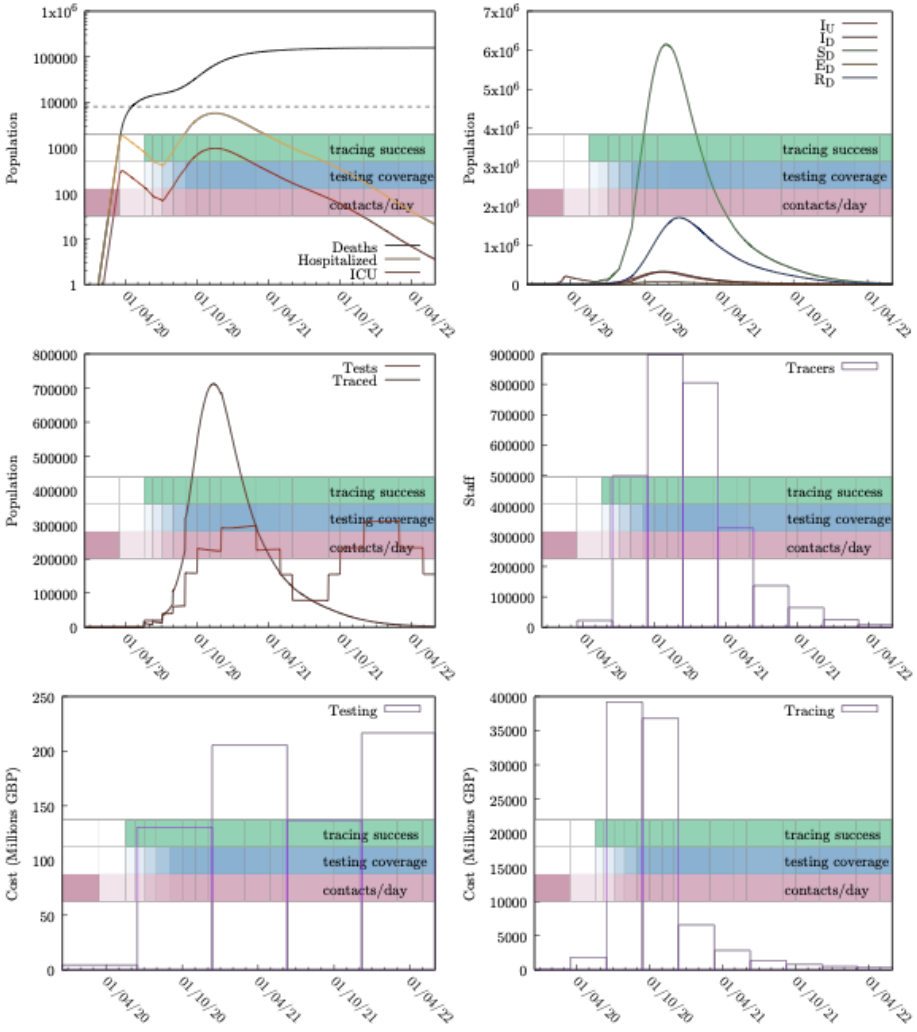


Figure S11 Targeted PTTI Lockdown Triggers trajectory

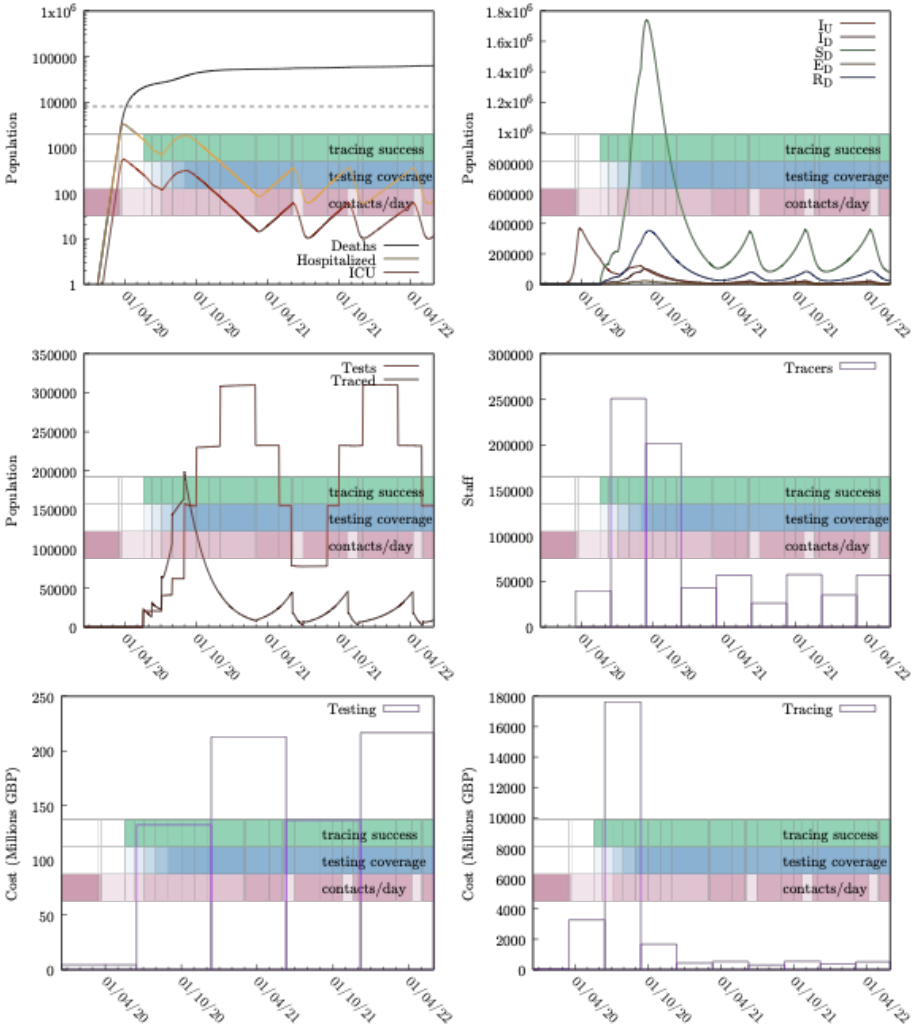


Figure S12 Targeted PTTI Face Coverings trajectory

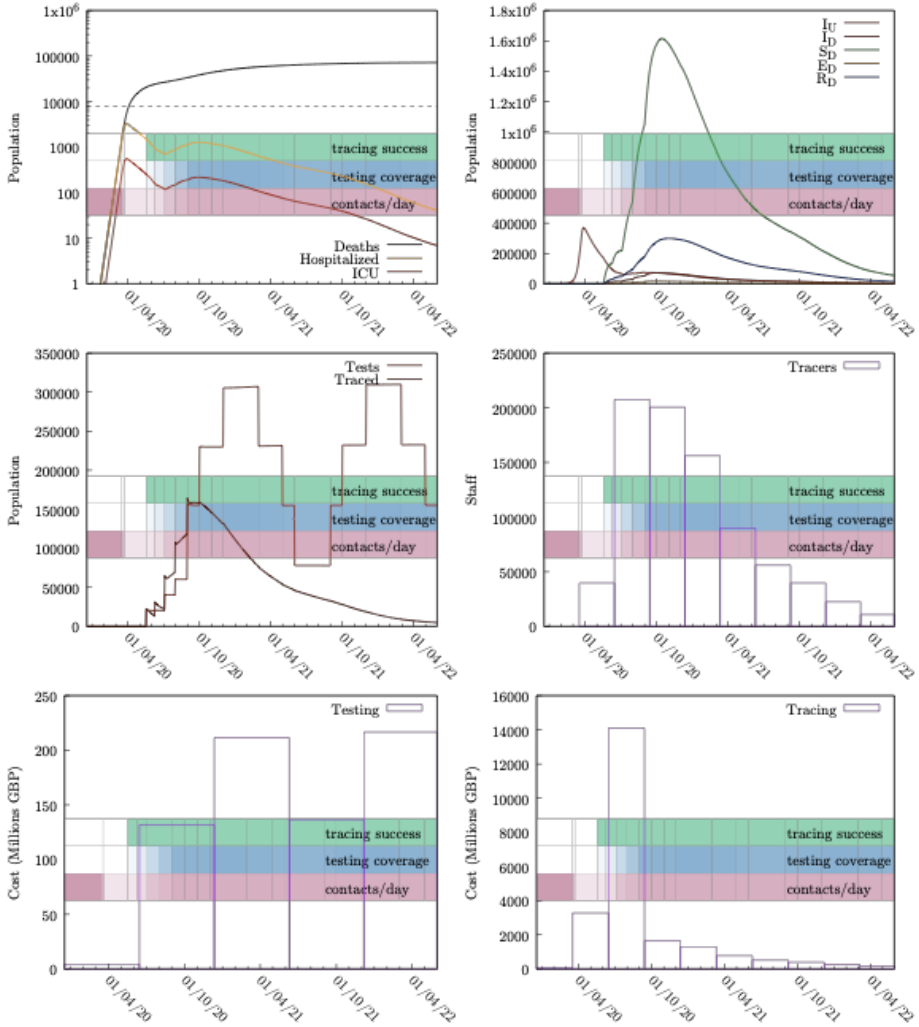


Figure S13 Targeted PTTI Face Coverings Lockdown Triggers trajectory

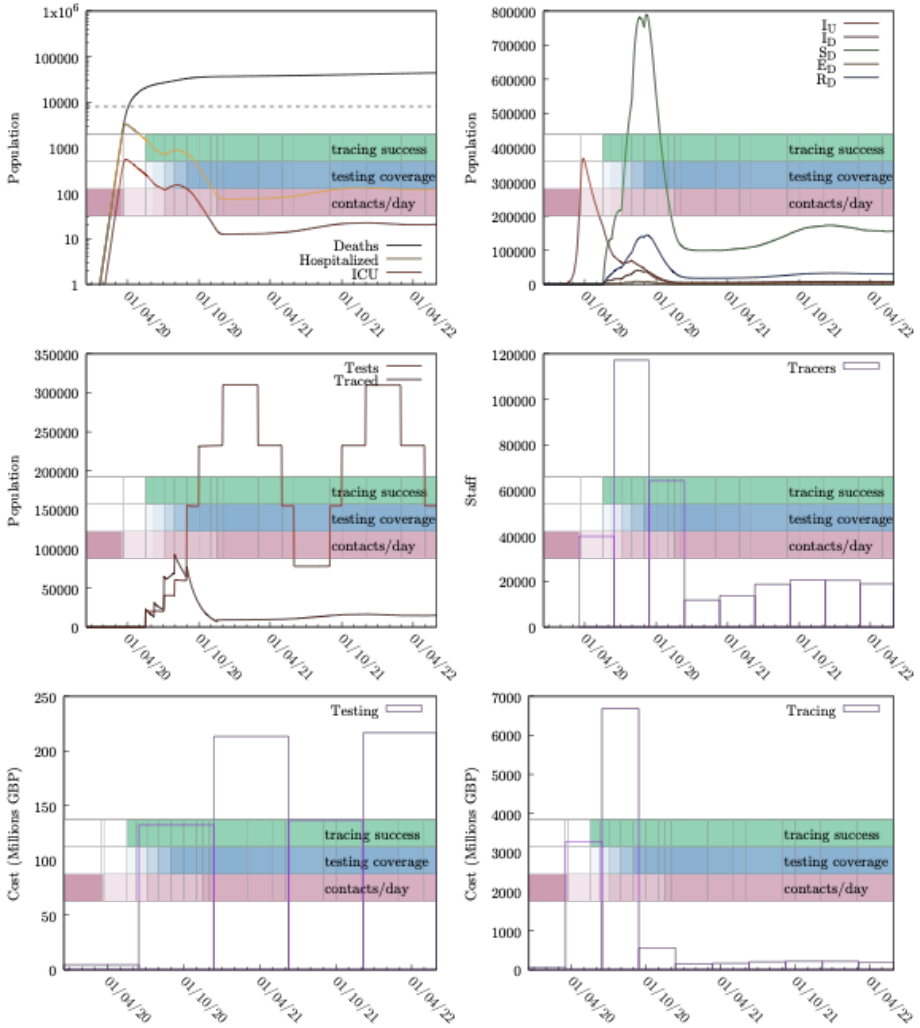


Figure S14 Targeted PTTI 30% Tracing Success Face Coverings Lockdown Tiggers trajectory

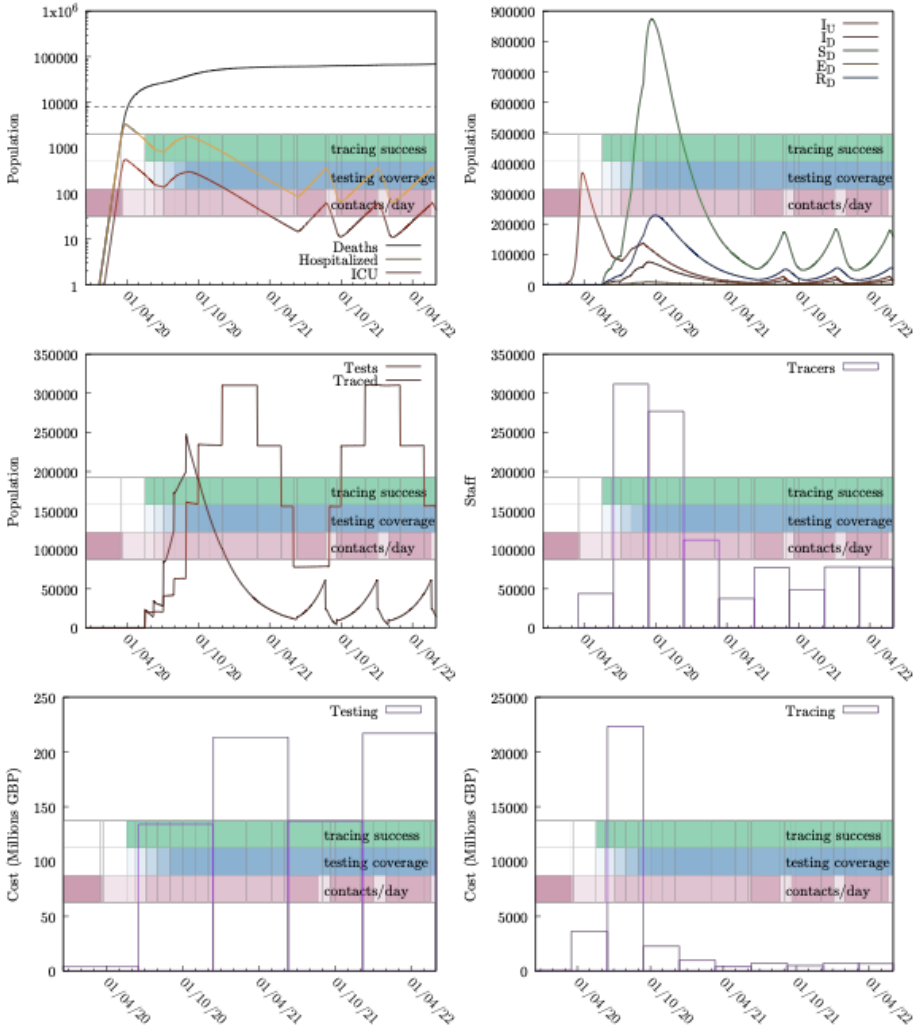


Figure S15 Targeted PTTI 40% Tracing Success Face Coverings Lockdown Tiggers trajectory

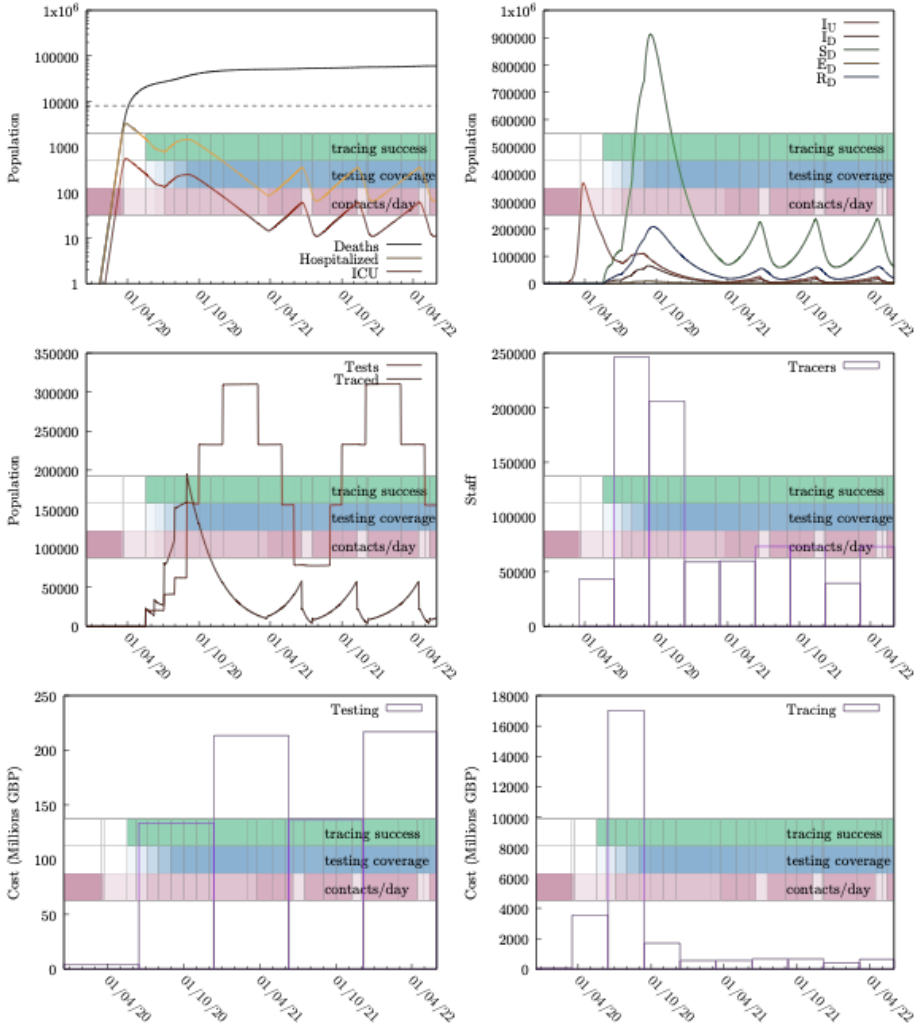
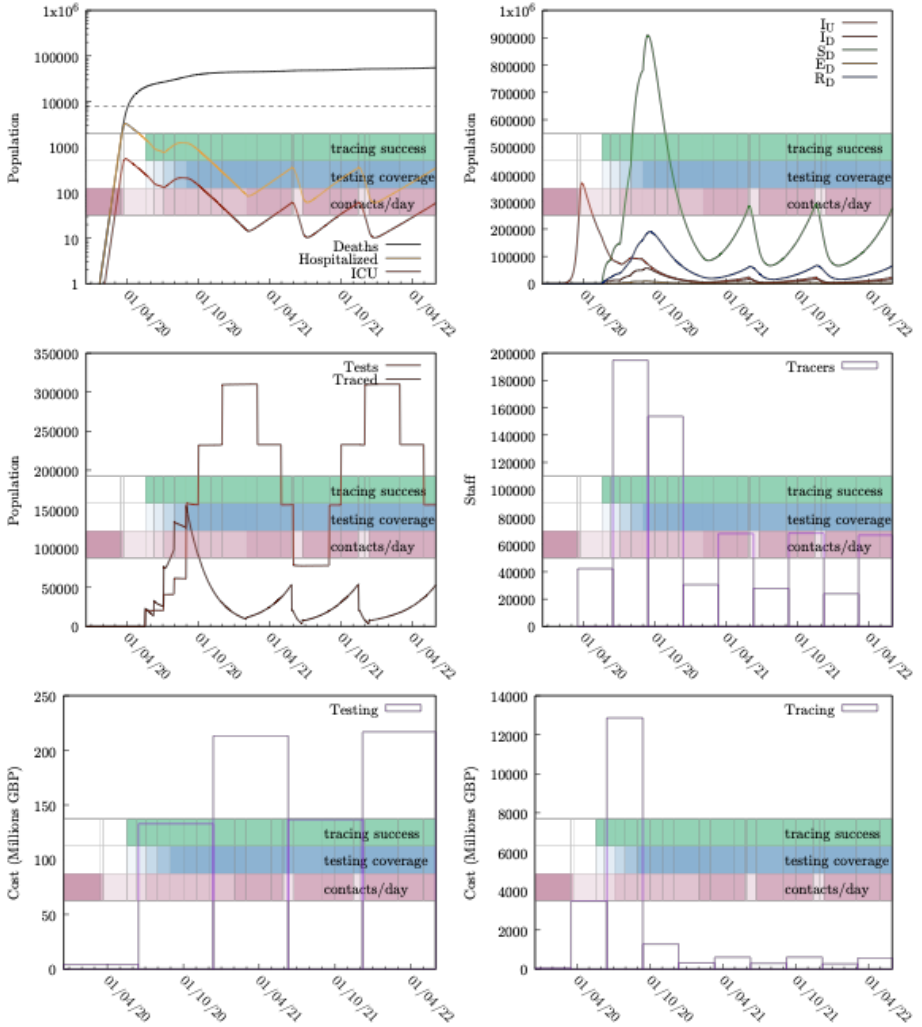


Figure S16 Targeted PTTI 50% Tracing Success Face Coverings Lockdown Tiggers trajectory



Lockdown triggers

Five 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 (Table S9) we see that additional lockdowns were triggered when there were no interventions (No TTI Lockdown Triggers, supplementary material Figure S2), when there was Untargeted PTTI (Untargeted PTTI Lockdown Triggers, one additional lockdown, Figure S4) , and when there was targeted testing (Targeted PTTI Lockdown Triggers, Figure S11). Additional lockdowns were not triggered in the Untargeted PTTI Face Coverings Lockdown Trigger or Targeted PTTI Face Coverings Lockdown Trigger scenarios.

Scenarios with lockdown triggers resulted in additional reduction in GDP compared to the same scenario without lockdown triggers (~£25bn – ~£676bn additional reduction in GDP; Table S9).

Face coverings

Including face coverings has a large estimated beneficial impact when untargeted testing, tracing and isolation is scaled-up to weekly testing during phased lockdown release (Untargeted PTTI Face Coverings relative to Untargeted PTTI, ~24,000 deaths averted, Table S10) 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, ~98,000 deaths averted, Table S10). With lockdown triggers, face coverings avert ~26,000 deaths for targeted PTTI though result in an additional ~3000 deaths for Untargeted PTTI because an additional lockdown is not triggered (cases stay below 40,000 with the face coverings) though it is triggered without the face coverings (at a cost of ~£32bn GDP reduction). Reduction in GDP is unaffected by face coverings and NHS costs are reduced in line with reduced cases, hospital cases, and ICU cases.

Untargeted large-scale testing vs. targeted testing of symptomatics

Table S11 shows that untargeted testing results in more deaths averted than targeted testing except for when both face coverings and lockdown triggers are added when they perform similarly. Untargeted testing has £27bn greater testing costs than targeted testing and, because it identifies more cases, greater tracing costs too.

Table S7 Full Scenario Results

	No TTI	No TTI Lockdown Triggers
Deaths	661,156	111,766
ICU cases	152,927	25,852
Hospital (non-ICU) cases	866,588	146,494
Non-hospital cases	58,424,409	9,876,451
NHS costs (£bn)	4.8	0.8
GDP reduction (£bn)	495.9	1,172.2
Public Health costs (£bn):	0.0	0.0
of which: Testing total costs (£bn)	0.0	0.0
Tracing total costs (£bn)	0.0	0.0

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Deaths	102,495	58,405	69,360	61,514	75,131	59,179	74,262
ICU cases	23,707	13,509	16,043	14,228	17,378	13,688	17,177
Hospital (non-ICU) cases	134,341	76,552	90,911	80,628	98,475	77,567	97,337
Non-hospital cases	9,057,146	5,161,053	6,129,148	5,435,819	6,639,106	5,229,473	6,562,334
NHS costs (£bn)	1	0.4	0.5	0.5	0.6	0.4	0.5

	Targeted PTTI	Targeted PTTI Lockdown Triggers	Targeted PTTI Face Coverings	Targeted PTTI Face Coverings Lockdown Triggers	Targeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Targeted PTTI 40% Tracing Success Face Coverings Lockdown Triggers	Targeted PTTI 50% Tracing Success Face Coverings Lockdown Triggers
GDP reduction (£bn)	495.9	553.5	495.9	521.4	588.9	553.1	683.7
Public Health costs (£bn):	181.8	48.7	91.2	58.2	28.2	64.6	43.9
of which: Testing total costs (£bn)	27.9	28.2	28.1	28.1	28.2	28.2	4.3
Tracing total costs (£bn)	**153.9**	**20.5**	**63.1**	**30.0**	**0**	**36.4**	**39.6**
Deaths	*216,517*	*86,121*	*99,119*	*60,334*	*94,763*	*82,956*	*76,005*
ICU cases	*50,081*	*19,920*	*22,927*	*13,955*	*21,919*	*19,188*	*17,580*
Hospital (non-ICU) cases	*283,792*	*112,880*	*129,917*	*79,080*	*124,207*	*108,732*	*99,621*
Non-hospital cases	*19,132,950*	*7,610,246*	*8,758,880*	*5,331,497*	*8,373,900*	*7,330,558*	*6,716,350*
NHS costs (£bn)	*1.6*	*0.6*	*0.7*	*0.4*	*0.7*	*0.6*	*0.6*
GDP reduction (£bn)	*502.8*	*673.7*	*495.9*	*537.3*	*704.5*	*684.4*	*630.8*
Public Health costs (£bn):	*91.0*	*26.0*	*23.2*	*12.4*	*33.0*	*26.5*	*21.1*
of which: Testing total costs (£bn)	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	*90.3*	*25.3*	*22.5*	*11.7*	*32.3*	*25.8*	*20.4*

Table S8 PTTI results **Comparison**	**Untargeted PTTI relative to No TTI**	With Lockdown triggers: Untargeted PTTI Lockdown Triggers relative to No TTI Lockdown Triggers	With face coverings: Untargeted PTTI Face Coverings relative to No TTI	**With face coverings & Lockdown triggers: Untargeted PTTI Face Coverings Lockdown Triggers relative to No TTI Lockdown Triggers**	Switching from untargeted to targeted relative to targeted only: Untargeted to Targeted PTTI Face coverings Lockdown Triggers relative to Targeted PTTI Face coverings Lockdown triggers
Deaths	**-558,661**	-53,361	-591,796	-50,252	-13,929
ICU cases	**-129,220**	-12,343	-136,884	-11,623	-3,222
Hospital (non-ICU) cases	**-732,247**	-69,942	-775,677	-65,866	-18,257
Non-hospital cases	**-49,367,263**	-4,715,398	-52,295,261	-4,440,632	-1,230,836
NHS costs (£bn)	**-4**	0	-4	0	0
Reduction in GDP (£bn)	**0**	-619	0	-651	-146
Public Health costs (£bn)	**182**	49	91	58	-31
of which: Testing total costs (£bn)	*28*	28	28	28	-4
Tracing total costs (£bn)	*154*	20	63	30	-28
Comparison	**With targetted testing (symptomatics only): Targetted PTTI relative to No TTI**	With targetted testing (symptomatics only) & Lockdown triggers: Targetted PTTI Lockdown Triggers relation to No TTI Lockdown Triggers	With face coverings: Targeted PTTI Face Coverings relative to No TTI	With targetted testing (symptomatics only) & Face coverings & Lockdown triggers: Targeted PTTI Face Coverings Lockdown Triggers relative to No TTI Lockdown Triggers	With targetted testing (symptomatics only): Targetted PTTI relative to No TTI

Deaths	**-444,639**	-25,645	-562,037	-51,433	-444,639
ICU cases	**-102,846**	-5,932	-130,001	-11,897	-102,846
Hospital (non-ICU) cases	**-582,796**	-33,614	-736,671	-67,414	-582,796
Non-hospital cases	**-39,291,459**	-2,266,205	-49,665,529	-4,544,954	-39,291,459
NHS costs (£bn)	**-3**	0	-4	0	-3
Reduction in GDP (£bn)	**7**	-498	0	-635	7
Public Health costs (£bn)	**91**	26	23	12	91
of which: Testing total costs (£bn)	*1*	1	1	1	1
Tracing total costs (£bn)	*90*	25	23	12	90

Table S9 Lockdown Trigger results **Comparison**	**No TTI Lockdown Triggers relative to No TTI**	Untargeted PTTI Lockdown Triggers relatiive to Untargeted PTTI	Untargeted PTTI Face Coverings Lockdown Triggers relative to Untargeted PTTI Face Coverings	Targeted PTTI Lockdown Triggers relative to Targeted PTTI	Targeted PTTI Face Coverings Lockdown Triggers relative to Targeted PTTI Face Coverings
Deaths	**-489,285**	**-34,772**	**-7,846**	**-110,713**	**-38,786**
ICU cases	**-113,173**	**-8,043**	**-1,815**	**-25,608**	**-8,971**
Hospital (non-ICU) cases	**-641,314**	**-45,576**	**-10,284**	**-145,113**	**-50,837**
Non-hospital cases	**-48,700,746**	**-3,919,779**	**-693,329**	**-11,572,739**	**-3,427,382**
NHS costs (£bn)	**-4**	**0**	**0**	**-1**	**0**
Reduction in GDP (£bn)	**676**	**58**	**25**	**171**	**41**
Public Health costs (£bn)	**0**	**-133**	**-33**	**-65**	**-11**
of which: Testing total costs (£bn)	***0***	**0**	**0**	**0**	**0**
Tracing total costs (£bn)	***0***	**-133**	**-33**	**-65**	**-11**

Table S10 Face coverings results

Comparison	**Untargeted PTTI Face Coverings relative to Untargeted PTTI**	Targeted PTTI Face Coverings relative to Targeted PTTI	Untargeted PTTI Face Coverings Lockdown Triggers relative to Untargetted PTTI Lockdown Triggers	Targeted PTTI Face Coverings Lockdown Triggers relative to Targetted PTTI Lockdown Triggers
Deaths	**-33,134**	-117,397	3,109	-25,787
ICU cases	**-7,664**	-27,154	719	-5,965
Hospital (non-ICU) cases	**-43,430**	-153,875	4,076	-33,800
Non-hospital cases	**-2,927,998**	-10,374,070	274,766	-2,278,749
NHS costs (£M)	**0**	-1	0	0
Reduction in GDP (£M)	**0**	-7	-32	-136
Public Health costs (£M)	**-91**	-68	10	-14
of which: Testing total costs (£M)	*0*	0	0	0
Tracing total costs (£M)	*-91*	-68	10	-14

Table S11 Untargeted large-scale testing vs. targeted testing of symptomatics

Comparison	**Untargeted PTTI relative to Targeted PTTI**	Untargeted PTTI Lockdown Triggers relative to Targeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings relative to Targeted PTTI Face Coverings	**Untargeted PTTI Face Coverings Lockdown Triggers relative to Targeted PTTI Face Coverings Lockdown Triggers**
Deaths	**-114,022**	-27,716	-29,759	1,181
ICU cases	**-26,374**	-6,411	-6,883	273
Hospital (non-ICU) cases	**-149,451**	-36,328	-39,006	1,547
Non-hospital cases	**-10,075,803**	-2,449,193	-2,629,732	104,322
NHS costs (£M)	**-1**	0	0	0
Reduction in GDP (£M)	**-7**	-120	0	-16
Public Health costs (£M)	**91**	23	68	46
of which: Testing total costs (£M)	*27*	27	27	27
Tracing total costs (£M)	*64*	-5	41	18

Sensitivity Analysis

GDP reduction during lockdown (base case 25%): 10%, 40%; face coverings effectiveness in reducing transmission (base case reduction in transmission per contact of 15%): 5%, 30%; proportion of infections that are symptomatic (base case 50%): 30%, 80%.

Table S12 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%

Table S13 Results with GDP 10% reductions

	No TTI	No TTI Lockdown Triggers
Reduction in GDP (£bn)	198.4	468.9

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Reduction in GDP (£bn)	198.4	221.4	198.4	208.6	235.6	221.2	273.5

	Targeted PTTI	*Targeted PTTI Lockdown Triggers*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*	*Targeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers*	*Targeted PTTI 40% Tracing Success Face Coverings Lockdown Triggers*	*Targeted PTTI 50% Tracing Success Face Coverings Lockdown Triggers*
Reduction in GDP (£bn)	*201.1*	*269.5*	*198.4*	*214.9*	*281.8*	*273.7*	*252.3*

Figure S17 Summary results with GDP 10% reductions

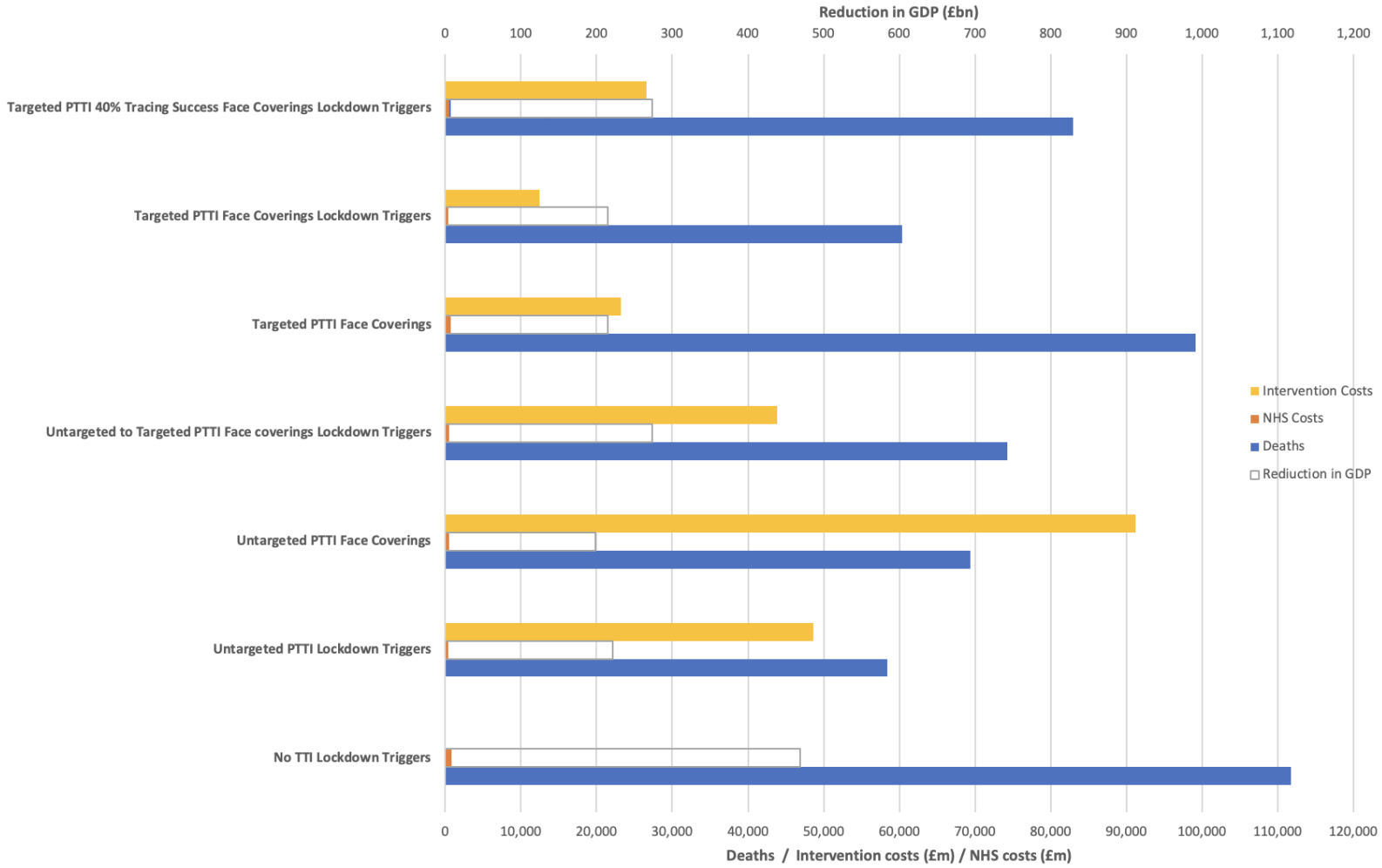


Table S14 Results with GDP 40% reductions

	No TTI	No TTI Lockdown Triggers
Reduction in GDP (£bn)	793.5	1,875.5

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Reduction in GDP (£bn)	793.5	885.6	793.5	834.2	942.3	884.9	1,093.9

	Targeted PTTI	*Targeted PTTI Lockdown Triggers*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*	*Targeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers*	*Targeted PTTI 40% Tracing Success Face Coverings Lockdown Triggers*	*Targeted PTTI 50% Tracing Success Face Coverings Lockdown Triggers*
Reduction in GDP (£bn)	*804.4*	*1,078.0*	*793.5*	*859.7*	*1,127.2*	*1,095.0*	*1,009.3*

Figure S18 Summary results with GDP 40% reductions

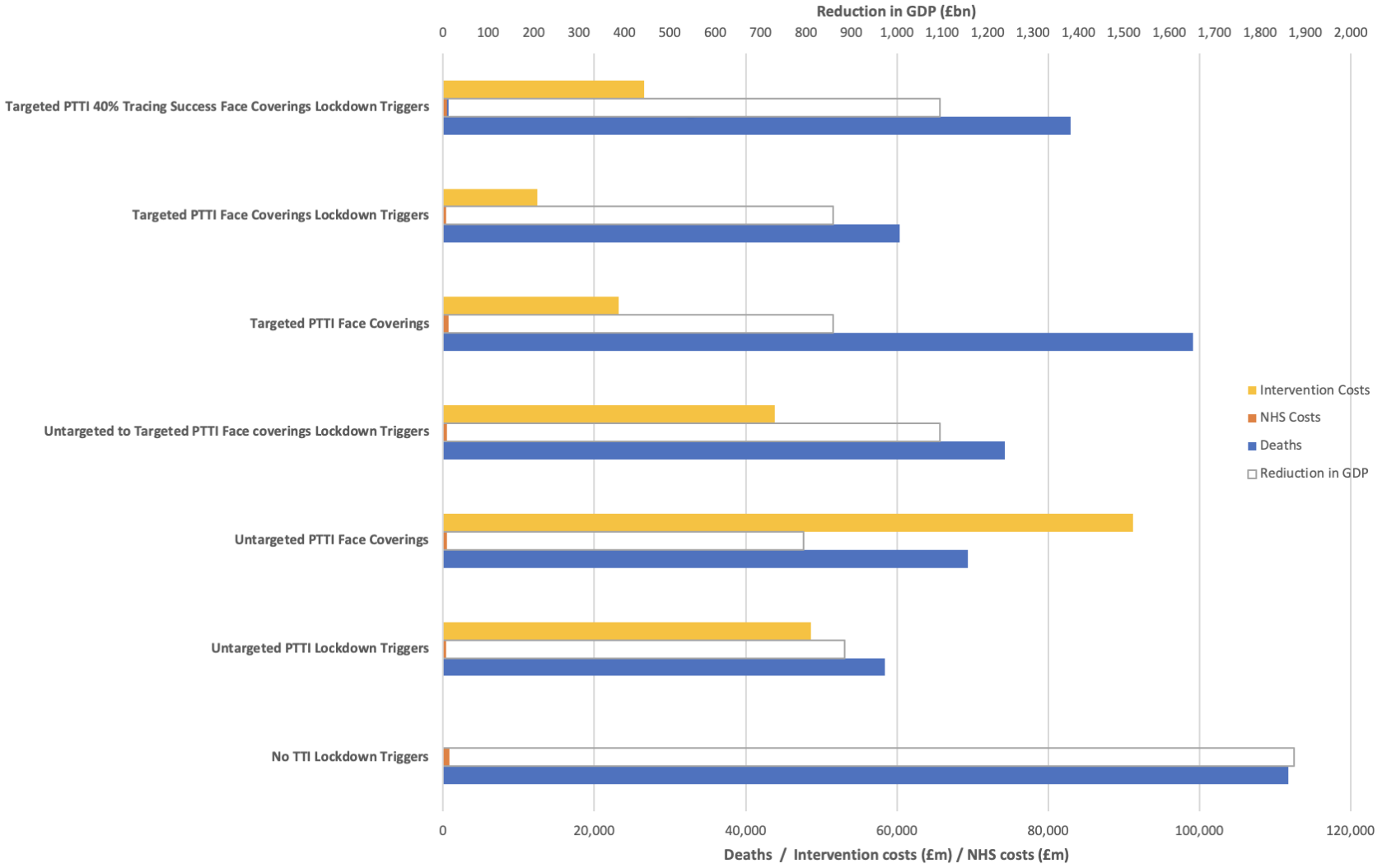


Table S15 Results with Face coverings 5% effective

To 31st May 2022	No TTI	No TTI Lockdown Triggers
Deaths	661,156	111,766
ICU cases	152,927	25,852
Hospital (non-ICU) cases	866,588	146,494
Non-hospital cases	58,424,409	9,876,451
NHS costs (£bn)	4.8	0.8
Reduction in GDP (£bn)	495.9	1,172.2
Public Health costs (£bn):	0.0	0.0
of which: Testing total costs (£bn)	0.0	0.0
Tracing total costs (£bn)	0.0	0.0

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Deaths	102,495	58,405	89,185	57,468	78,748	59,870	77,303
ICU cases	23,707	13,509	20,629	13,292	18,215	13,848	17,880
Hospital (non-ICU) cases	134,341	76,552	116,897	75,324	103,217	78,473	101,323
Non-hospital cases	9,057,146	5,161,053	7,881,038	5,078,246	6,958,768	5,290,568	6,831,068
NHS costs (£bn)	1	0.4	0.7	0.4	0.6	0.4	0.6
Reduction in GDP (£bn)	495.9	553.5	495.9	521.4	588.9	553.1	683.7
Public Health costs (£bn):	181.8	48.7	144.4	64.5	58.3	51.3	31.1
of which: Testing total costs (£bn)	27.9	28.2	28.0	28.2	28.2	28.2	4.3
Tracing total costs (£bn)	153.9	20.5	116.4	36.3	30.1	23.1	26.8

	Targeted PTTI	Targeted PTTI Lockdown Triggers	Targeted PTTI Face Coverings	Targeted PTTI Face Coverings Lockdown Triggers	Targeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Targeted PTTI 40% Tracing Success Face Coverings Lockdown Triggers	Targeted PTTI 50% Tracing Success Face Coverings Lockdown Triggers
Deaths	*216,517*	*86,121*	*181,925*	*75,498*	*81,211*	*83,155*	*107,100*
ICU cases	*50,081*	*19,920*	*42,080*	*17,463*	*18,784*	*19,234*	*24,772*
Hospital (non-ICU) cases	*283,792*	*112,880*	*238,452*	*98,956*	*106,445*	*108,993*	*140,377*
Non-hospital cases	*19,132,950*	*7,610,246*	*16,076,149*	*6,671,497*	*7,176,369*	*7,348,198*	*9,464,076*
NHS costs (£bn)	*1.6*	*0.6*	*1.3*	*0.6*	*0.6*	*0.6*	*0.8*
Reduction in GDP (£bn)	*502.8*	*673.7*	*495.9*	*537.3*	*704.5*	*684.4*	*630.8*
Public Health costs (£bn):	*91.0*	*26.0*	*58.8*	*19.5*	*38.5*	*36.8*	*38.4*
of which: Testing total costs (£bn)	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	*90.3*	*25.3*	*58.1*	*18.8*	*37.8*	*36.1*	*37.7*

Figure S19 Summary results with Face coverings 5% effective

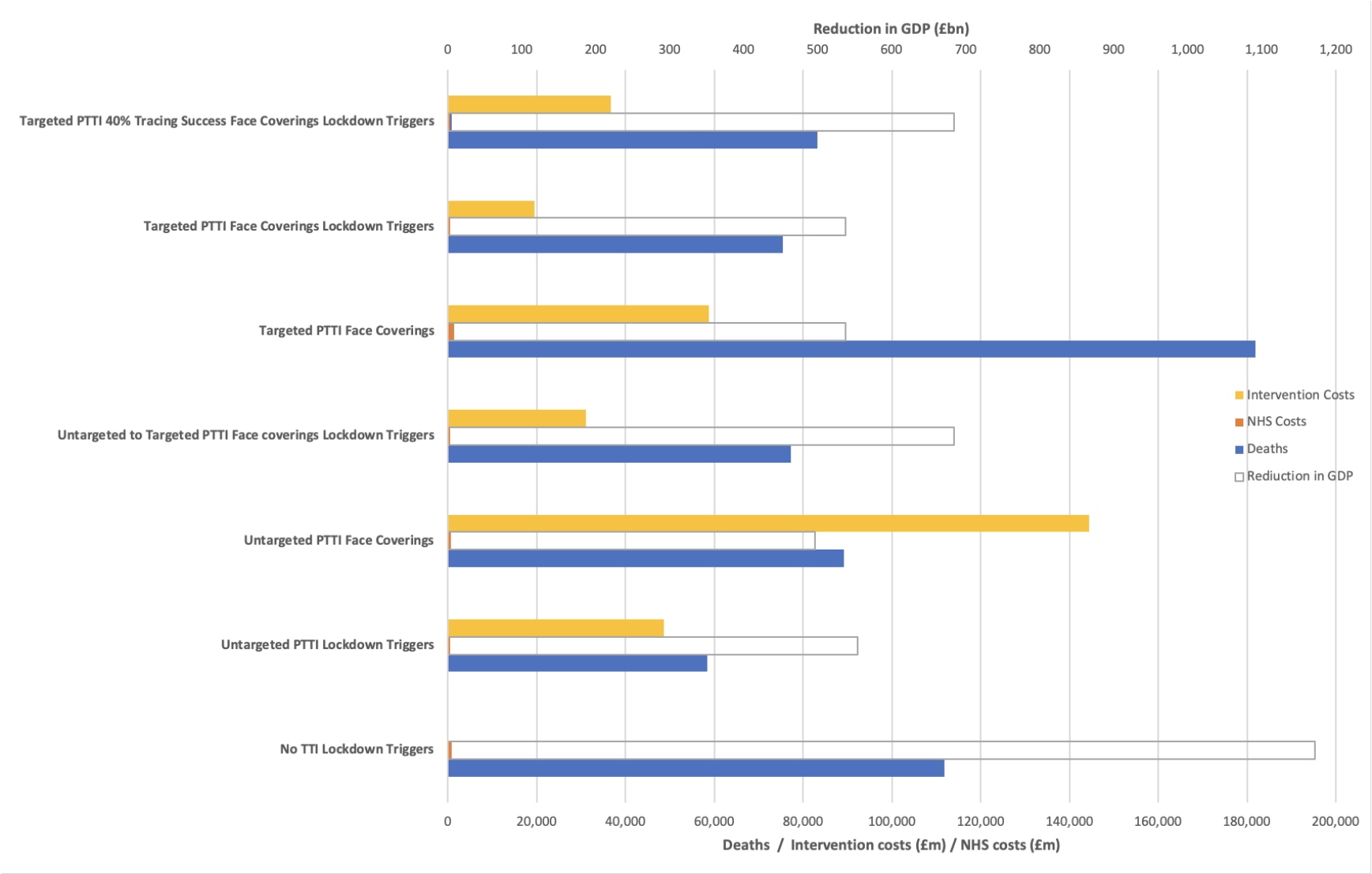


Table S16 Results with Face coverings 30% effective

To 31st May 2022	No TTI	No TTI Lockdown Triggers
Deaths	661,156	111,766
ICU cases	152,927	25,852
Hospital (non-ICU) cases	866,588	146,494
Non-hospital cases	58,424,409	9,876,451
NHS costs (£bn)	4.8	0.8
Reduction in GDP (£bn)	495.9	1,172.2
Public Health costs (£bn):	0.0	0.0
of which: Testing total costs (£bn)	0.0	0.0
Tracing total costs (£bn)	0.0	0.0

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Deaths	102,495	58,405	53,053	50,588	62,449	55,613	59,267
ICU cases	23,707	13,509	12,271	11,701	14,445	12,863	13,709
Hospital (non-ICU) cases	134,341	76,552	69,537	66,306	81,854	72,893	77,682
Non-hospital cases	9,057,146	5,161,053	4,688,096	4,470,285	5,518,479	4,914,361	5,237,255
NHS costs (£bn)	1	0.4	0.4	0.4	0.5	0.4	0.4
Reduction in GDP (£bn)	495.9	553.5	495.9	521.4	588.9	553.1	683.7
Public Health costs (£bn):	181.8	48.7	50.4	45.4	78.0	55.8	32.3
of which: Testing total costs (£bn)	27.9	28.2	28.2	28.2	28.2	28.2	4.3
Tracing total costs (£bn)	153.9	20.5	22.2	17.2	49.8	27.6	28.1

	Targeted PTTI	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings*	*Targeted PTTI 30% Tracing Success Face*	*Targeted PTTI 40% Tracing Success Face*	*Targeted PTTI 50% Tracing*

		Lockdown Triggers		*Lockdown Triggers*	*Coverings Lockdown Triggers*	*Coverings Lockdown Triggers*	*Success Face Coverings Lockdown Triggers*
Deaths	*216,517*	*86,121*	*46,644*	*43,782*	*67,592*	*53,119*	*48,275*
ICU cases	*50,081*	*19,920*	*10,789*	*10,127*	*15,634*	*12,286*	*11,166*
Hospital (non-ICU) cases	*283,792*	*112,880*	*61,137*	*57,386*	*88,594*	*69,623*	*63,275*
Non-hospital cases	*19,132,950*	*7,610,246*	*4,121,758*	*3,868,929*	*5,972,894*	*4,693,930*	*4,265,906*
NHS costs (£bn)	*1.6*	*0.6*	*0.3*	*0.3*	*0.5*	*0.4*	*0.4*
Reduction in GDP (£bn)	*502.8*	*673.7*	*495.9*	*537.3*	*704.5*	*684.4*	*630.8*
Public Health costs (£bn):	*91.0*	*26.0*	*8.9*	*8.3*	*15.2*	*12.2*	*10.6*
of which: Testing total costs(£bn)	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	*90.3*	*25.3*	*8.2*	*7.6*	*14.5*	*11.5*	*9.9*

Figure S20 Summary results with Face coverings 30% effective

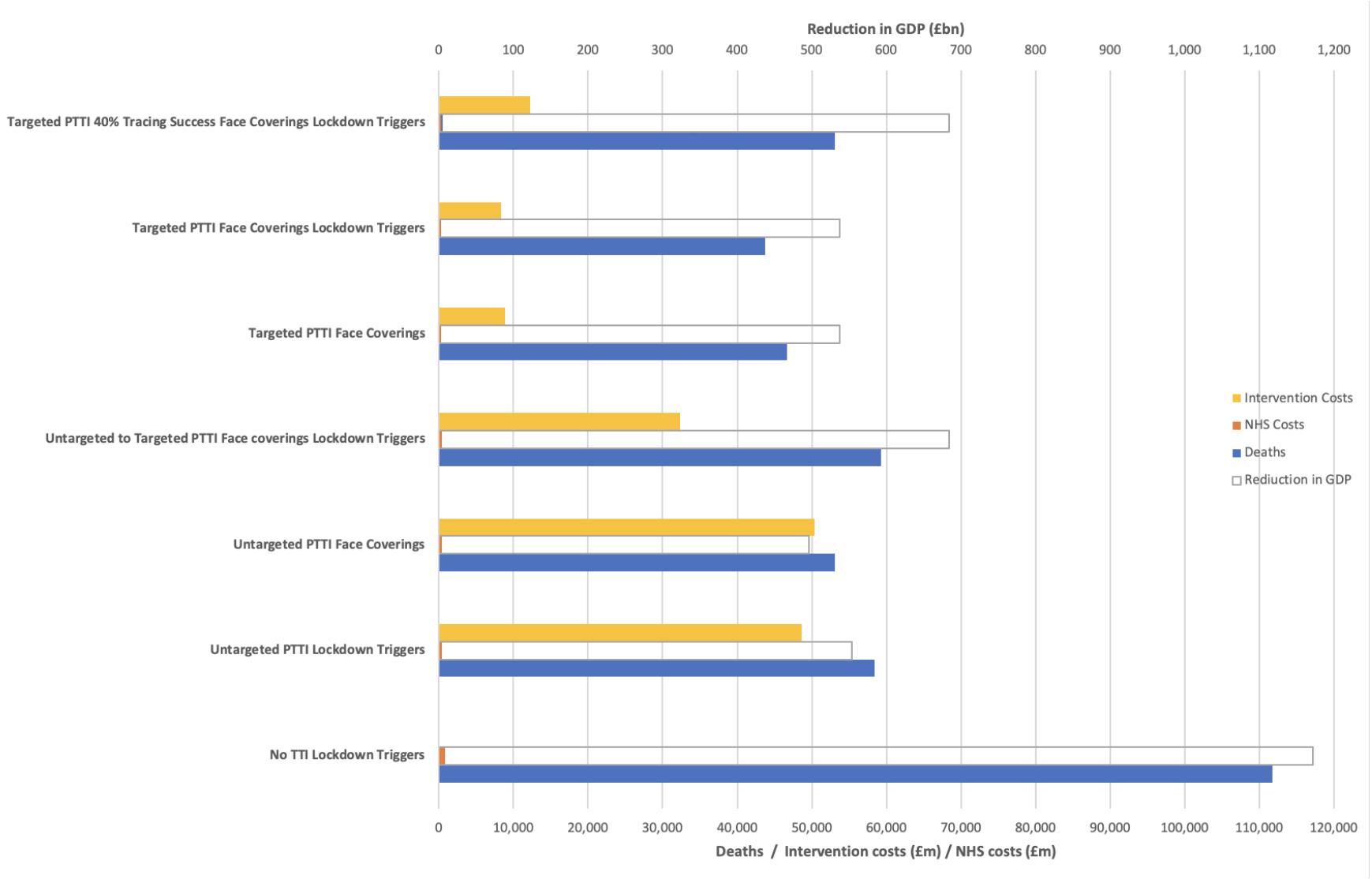


Table S17 Results with 30% Symptomatic

To 31st May 2022	No TTI	No TTI Lockdown Triggers
Deaths	661,156	111,766
ICU cases	152,927	25,852
Hospital (non-ICU) cases	866,588	146,494
Non-hospital cases	58,424,409	9,876,451
NHS costs (£bn)	4.8	0.8
Reduction in GDP (£bn)	495.9	1,172.2
Public Health costs (£bn):	0.0	0.0
of which: Testing total costs (£bn)	0.0	0.0
Tracing total costs (£bn)	0.0	0.0

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Deaths	102,495	58,405	69,360	61,514	75,131	59,179	76,981
ICU cases	23,707	13,509	16,043	14,228	17,378	13,688	17,806
Hospital (non-ICU) cases	134,341	76,552	90,911	80,628	98,475	77,567	100,900
Non-hospital cases	9,057,146	5,161,053	6,129,148	5,435,819	6,639,106	5,229,473	6,802,545
NHS costs (£bn)	1	0.4	0.5	0.5	0.6	0.4	0.6
Reduction in GDP (£bn)	495.9	553.5	495.9	521.4	588.9	553.1	683.7
Public Health costs (£bn):	181.8	48.7	91.2	58.2	75.4	64.6	43.8
of which: Testing total costs (£bn)	27.9	28.2	28.1	28.1	28.2	28.2	4.3
Tracing total costs (£bn)	153.9	20.5	63.1	30.0	47.2	36.4	39.5

	Targeted PTTI	*Targeted PTTI Lockdown Triggers*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings*	*Targeted PTTI 30% Tracing Success Face*	*Targeted PTTI 40% Tracing Success Face*	*Targeted PTTI 50% Tracing Success Face*

				Lockdown Triggers	*Coverings Lockdown Triggers*	*Coverings Lockdown Triggers*	*Coverings Lockdown Triggers*
Deaths	*349,789*	*80,420*	*265,826*	*101,684*	*83,275*	*83,105*	*84,058*
ICU cases	*80,907*	*18,601*	*61,486*	*23,520*	*19,262*	*19,222*	*19,443*
Hospital (non-ICU) cases	*458,474*	*105,408*	*348,423*	*133,278*	*109,150*	*108,927*	*110,177*
Non-hospital cases	*30,909,807*	*7,106,494*	*23,490,296*	*8,985,479*	*7,358,747*	*7,343,723*	*7,427,988*
NHS costs (£bn)	*2.6*	*0.6*	*1.9*	*0.7*	*0.6*	*0.6*	*0.6*
Reduction in GDP (£bn)	*502.8*	*673.7*	*495.9*	*537.3*	*704.5*	*684.4*	*630.8*
Public Health costs (£bn):	*239.4*	*27.2*	*109.1*	*25.4*	*30.4*	*29.4*	*28.5*
of which: Testing total costs (£bn)	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	*238.7*	*26.5*	*108.4*	*24.7*	*29.7*	*28.7*	*27.8*

Figure S21 Summary results with 30% symptomatic

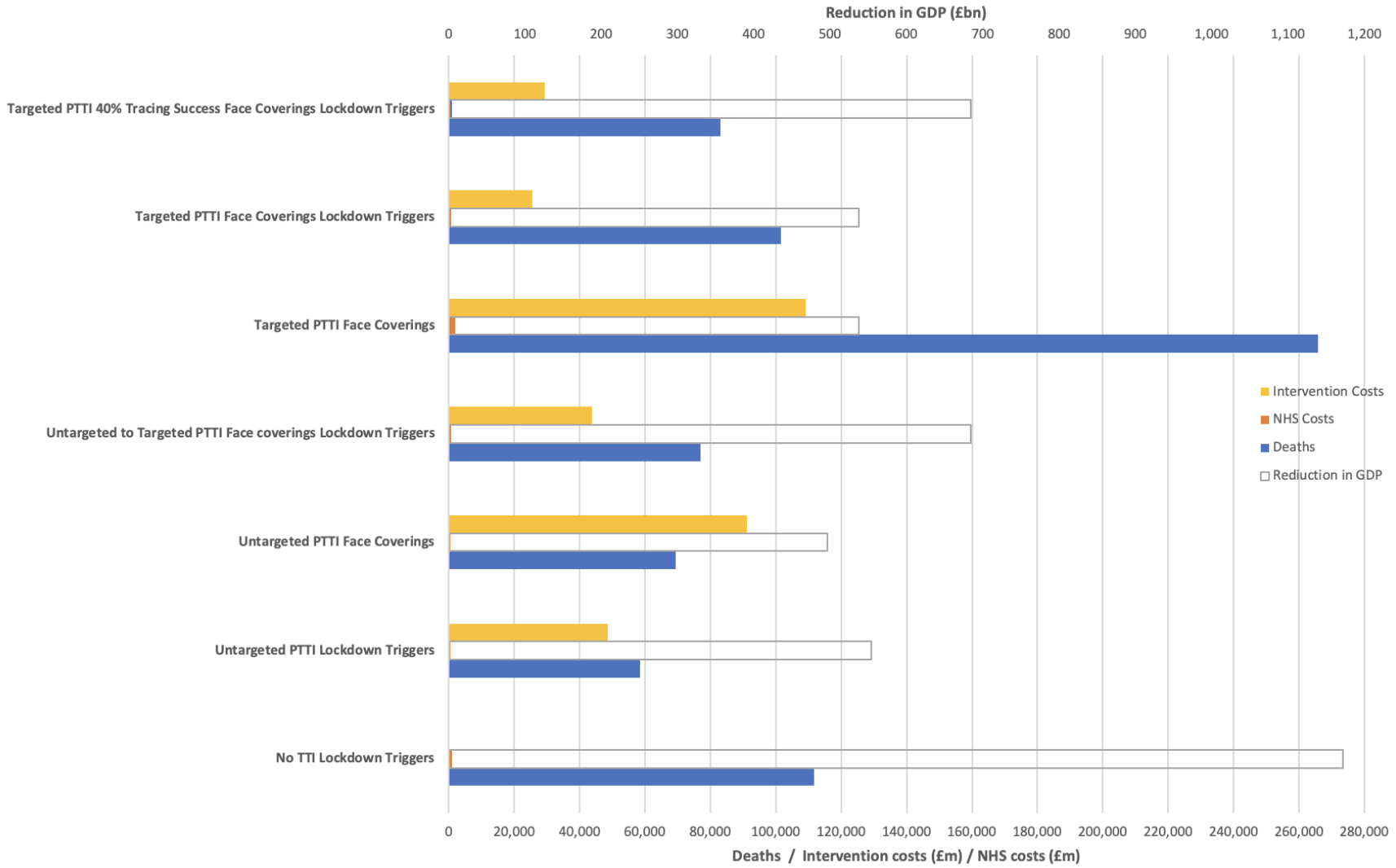


Table S18 Results with 80% Symptomatic

To 31st May 2022	No TTI	No TTI Lockdown Triggers
Deaths	661,156	111,766
ICU cases	152,927	25,852
Hospital (non-ICU) cases	866,588	146,494
Non-hospital cases	58,424,409	9,876,451
NHS costs (£bn)	4.8	0.8
Reduction in GDP (£bn)	495.9	1,172.2
Public Health costs (£bn):	0.0	0.0
of which: Testing total costs (£bn)	0.0	0.0
Tracing total costs (£bn)	0.0	0.0

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Deaths	102,495	58,405	69,360	61,514	75,131	59,179	60,088
ICU cases	23,707	13,509	16,043	14,228	17,378	13,688	13,899
Hospital (non-ICU) cases	134,341	76,552	90,911	80,628	98,475	77,567	78,759
Non-hospital cases	9,057,146	5,161,053	6,129,148	5,435,819	6,639,106	5,229,473	5,309,820
NHS costs (£bn)	1	0.4	0.5	0.5	0.6	0.4	0.4
Reduction in GDP (£bn)	495.9	553.5	495.9	521.4	588.9	553.1	683.7
Public Health costs (£bn):	181.8	48.7	91.2	58.2	75.4	64.6	40.8
of which: Testing total costs (£bn)	27.9	28.2	28.1	28.1	28.2	28.2	4.3
Tracing total costs (£bn)	153.9	20.5	63.1	30.0	47.2	36.4	36.5

	Targeted PTTI	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings*	*Targeted PTTI 30% Tracing Success Face*	*Targeted PTTI 40% Tracing Success Face*	*Targeted PTTI 50% Tracing Success Face*

		Lockdown Triggers		Lockdown Triggers	Coverings Lockdown Triggers	Coverings Lockdown Triggers	Coverings Lockdown Triggers
Deaths	*33,417*	*44,798*	*42,302*	*41,144*	*58,464*	*48,025*	*44,998*
ICU cases	*7,730*	*10,362*	*9,785*	*9,517*	*13,523*	*11,108*	*10,408*
Hospital (non-ICU) cases	*43,801*	*58,717*	*55,446*	*53,928*	*76,630*	*62,947*	*58,980*
Non-hospital cases	*2,952,981*	*3,958,657*	*3,738,140*	*3,635,783*	*5,166,284*	*4,243,832*	*3,976,345*
NHS costs (£bn)	*0.2*	*0.3*	*0.3*	*0.3*	*0.4*	*0.4*	*0.3*
Reduction in GDP (£bn)	*502.8*	*673.7*	*495.9*	*537.3*	*704.5*	*684.4*	*630.8*
Public Health costs (£bn):	*9.1*	*9.7*	*8.1*	*7.9*	*16.6*	*13.1*	*10.9*
of which: Testing total costs (£bn)	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	*8.4*	*9.0*	*7.4*	*7.2*	*15.9*	*12.4*	*10.1*

Figure S22 Summary results with 80% symptomatic

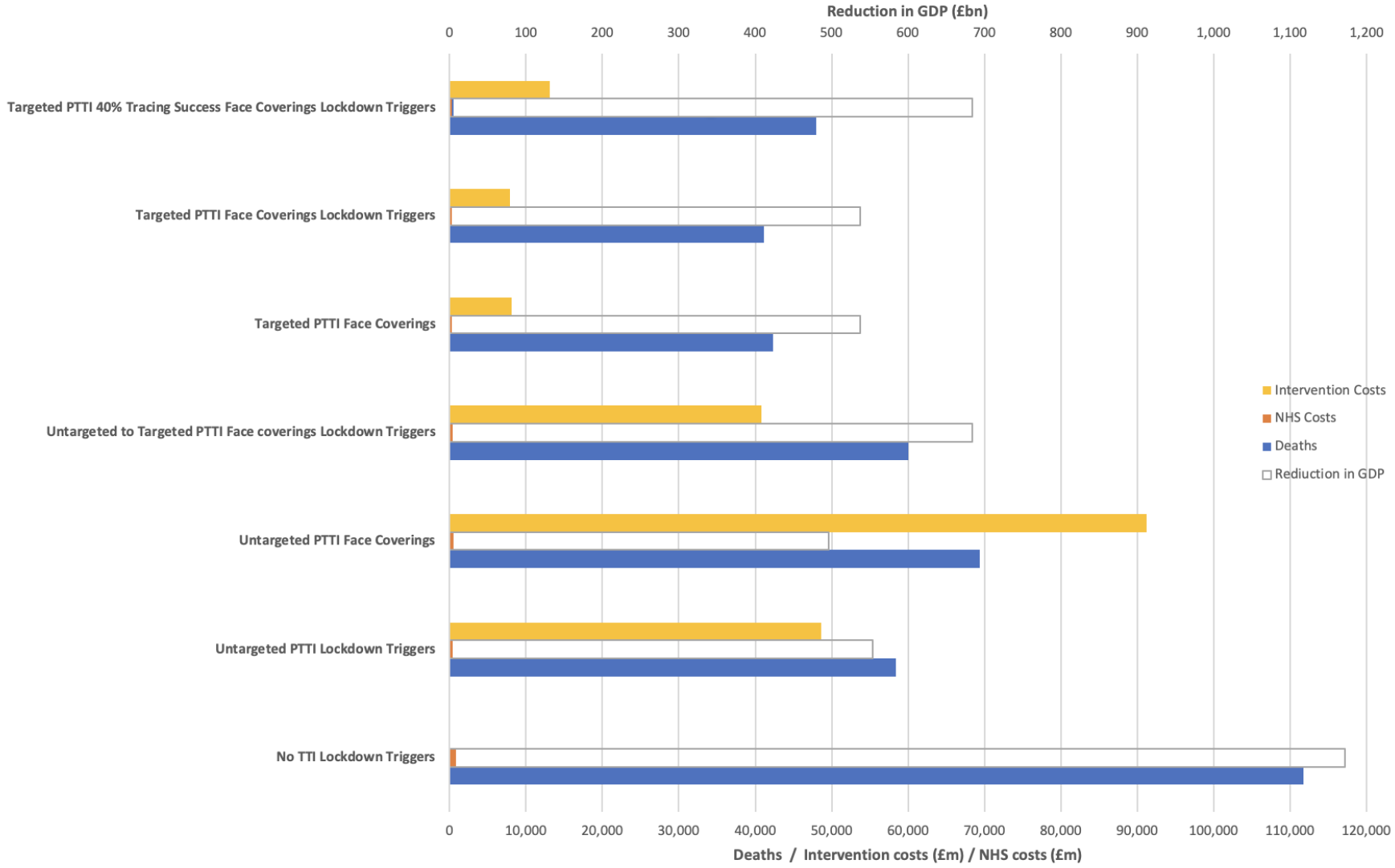


Table S19 Results with 5 day infectious period

To 31st May 2022	No TTI
Deaths	656,430
ICU cases	151,834
Hospital (non-ICU) cases	860,394
Non-hospital cases	58,006,799
NHS costs (£bn)	4.8
Reduction in GDP (£bn)	495.9
Public Health costs (£bn):	0.0
of which: Testing total costs (£bn)	0.0
Tracing total costs (£bn)	0.0

	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Deaths	154,207	71,983	92,437	76,873	100,257	74,770	98,411
ICU cases	35,669	16,650	21,381	17,781	23,190	17,294	22,763
Hospital (non-ICU) cases	202,122	94,350	121,159	100,758	131,408	98,002	128,989
Non-hospital cases	13,626,833	6,360,970	8,168,396	6,793,024	8,859,397	6,607,187	8,696,303
NHS costs (£bn)	1	0.5	0.7	0.6	0.7	0.5	0.7
Reduction in GDP (£bn)	495.9	553.5	495.9	521.4	588.9	553.1	683.7
Public Health costs (£bn):	128.5	39.4	64.1	46.6	51.1	56.5	22.8
of which: Testing total costs (£bn)	27.9	28.1	28.0	28.1	28.1	28.1	4.3
Tracing total costs (£bn)	100.6	11.2	36.0	18.5	22.9	28.4	18.5

	Targeted PTTI	*Targeted PTTI*	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings*	*Targeted PTTI 30% Tracing Success Face*	*Targeted PTTI 40% Tracing Success*	*Targeted PTTI 50% Tracing Success*

		Lockdown Triggers		*Lockdown Triggers*	*Coverings Lockdown Triggers*	*Face Coverings Lockdown Triggers*	*Face Coverings Lockdown Triggers*
Deaths	*303,467*	*107,782*	*198,285*	*87,021*	*158,770*	*131,027*	*112,486*
ICU cases	*70,193*	*24,930*	*45,864*	*20,128*	*36,724*	*30,307*	*26,018*
Hospital (non-ICU) cases	*397,760*	*141,271*	*259,895*	*114,061*	*208,102*	*171,739*	*147,437*
Non-hospital cases	*26,816,501*	*9,524,365*	*17,521,850*	*7,689,832*	*14,030,025*	*11,578,463*	*9,940,017*
NHS costs (£bn)	*2.2*	*0.8*	*1.5*	*0.6*	*1.2*	*1.0*	*0.8*
Reduction in GDP (£bn)	*502.8*	*673.7*	*495.9*	*537.3*	*704.5*	*684.4*	*630.8*
Public Health costs (£bn):	*144.6*	*28.5*	*44.3*	*10.7*	*33.5*	*26.1*	*20.7*
of which: Testing total costs (£bn)	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	*143.9*	*27.8*	*43.6*	*10.0*	*32.8*	*25.4*	*20.0*

Figure S23 Summary results with 5 day infectious period

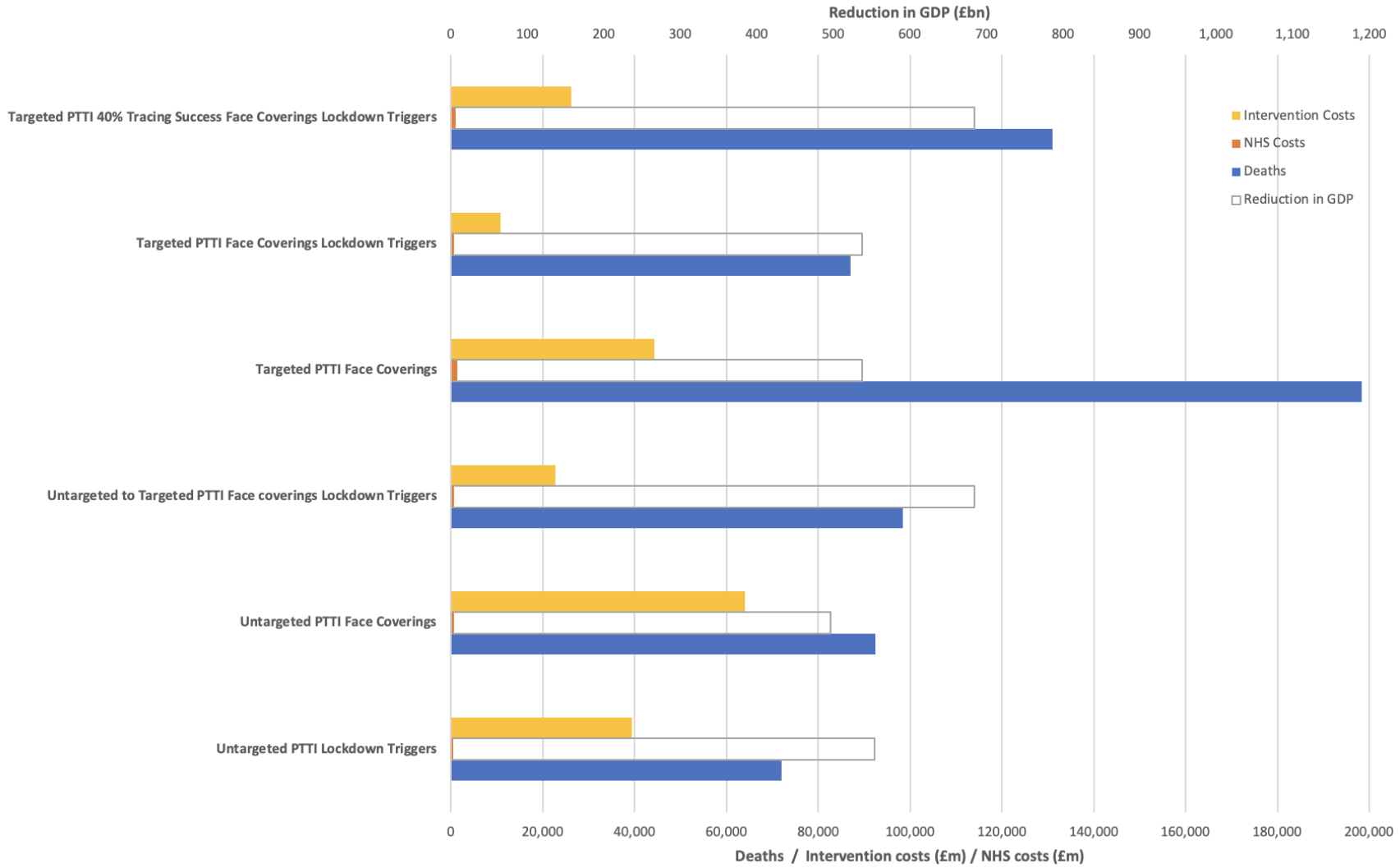


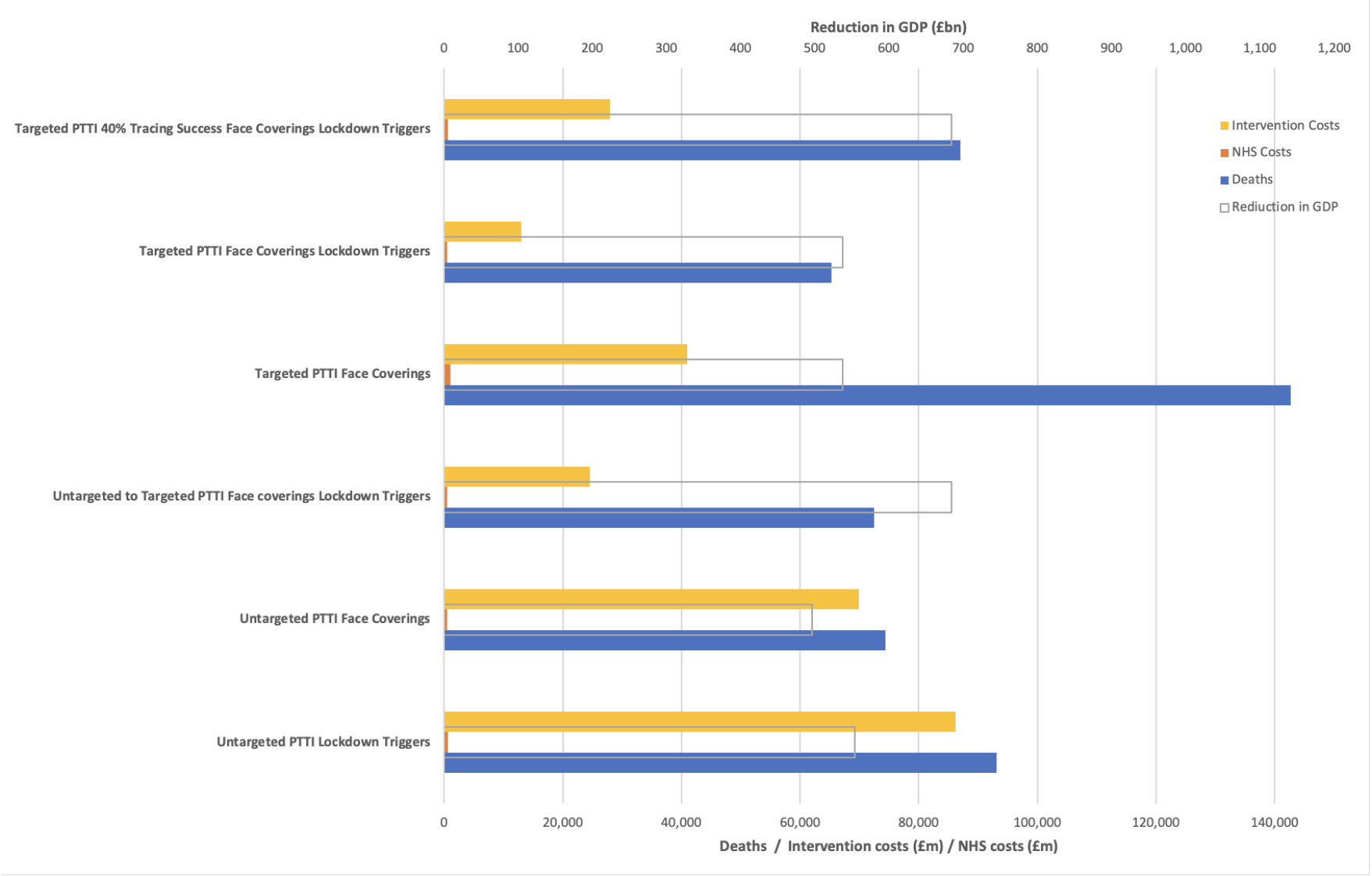
Table S20 Results with 3 day latent period

To 31st May 2022	No TTI
Deaths	658,128
ICU cases	152,227
Hospital (non-ICU) cases	862,620
Non-hospital cases	58,156,868
NHS costs (£bn)	4.8
Reduction in GDP (£bn)	495.9
Public Health costs (£bn):	0.0
of which: Testing total costs (£bn)	0.0
Tracing total costs (£bn)	0.0

Targeted PTTI	Untargeted PTTI	Untargeted PTTI Lockdown Triggers	Untargeted PTTI Face Coverings	Untargeted PTTI Face Coverings Lockdown Triggers	Untargeted PTTI 0% Tracing Success Face Coverings Lockdown Triggers	Untargeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers	Untargeted to Targeted PTTI Face coverings Lockdown Triggers
Deaths	121,400	93,139	74,371	63,255	70,688	56,291	72,402
ICU cases	28,080	21,543	17,202	14,631	16,350	13,020	16,747
Hospital (non-ICU) cases	159,121	122,078	97,479	82,909	92,651	73,781	94,898
Non-hospital cases	10,727,734	8,230,395	6,571,907	5,589,657	6,246,451	4,974,227	6,397,937
NHS costs (£bn)	1	0.7	0.5	0.5	0.5	0.4	0.5
Reduction in GDP (£bn)	495.9	553.5	495.9	521.4	588.9	553.1	683.7
Public Health costs (£bn):	143.4	86.2	69.9	55.4	48.0	43.6	24.5
of which: Testing total costs (£bn)	27.9	28.0	28.1	28.1	28.2	28.2	4.3
Tracing total costs (£bn)	115.5	58.2	41.9	27.3	19.8	15.4	20.2

		Targeted PTTI Lockdown Triggers	*Targeted PTTI Face Coverings*	*Targeted PTTI Face Coverings Lockdown Triggers*	*Targeted PTTI 30% Tracing Success Face Coverings Lockdown Triggers*	*Targeted PTTI 40% Tracing Success Face Coverings Lockdown Triggers*	*Targeted PTTI 50% Tracing Success Face Coverings Lockdown Triggers*
Deaths	*244,068*	*100,553*	*142,687*	*65,267*	*100,205*	*87,014*	*78,430*
ICU cases	*56,454*	*23,258*	*33,004*	*15,096*	*23,178*	*20,127*	*18,141*
Hospital (non-ICU) cases	*319,904*	*131,796*	*187,022*	*85,546*	*131,340*	*114,051*	*102,799*
Non-hospital cases	*21,567,590*	*8,885,545*	*12,608,847*	*5,767,445*	*8,854,828*	*7,689,180*	*6,930,624*
NHS costs (£bn)	*1.8*	*0.7*	*1.0*	*0.5*	*0.7*	*0.6*	*0.6*
Reduction in GDP (£bn)	*502.8*	*673.7*	*495.9*	*537.3*	*704.5*	*684.4*	*630.8*
Public Health costs (£bn):	*155.2*	*33.5*	*41.0*	*12.9*	*35.8*	*27.9*	*21.8*
of which: Testing total costs (£bn)	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*	*0.7*
Tracing total costs (£bn)	*154.5*	*32.8*	*40.3*	*12.2*	*35.1*	*27.2*	*21.1*

Figure S24 Summary results with 3 day latent period



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