Supplementary material to
"Modelling the health and economic impacts of different testing and tracing strategies for COVID-19 in the UK"

Epidemiological model and calibration

Details of the compartmental SEIR-TTI model we used for the impact analysis are in Sturniolo et al.[1] In summary, it is an extended version of the classic SEIR model that incorporates probabilistically the effects of testing, contact tracing, and isolation. For the purposes of the analysis here, we fixed the majority of the model parameters to the values from the literature as per Table S1. We fitted the four parameters: transmission probability β, the rate of contacts, the date of the onset of the epidemic, number of infectious people at the onset of the epidemic and the infection fatality rate (IFR) to match the model projected deaths to the publicly available mortality data from the UK government (https://coronavirus.data.gov.uk/). To match the UK epidemic we consider a single infectious individual introduced into the UK in late December 2019. This is simply a mathematical convenience and not a claim about the seeding of the actual epidemic in the UK. It is not our purpose to investigate the origins of the epidemic in this article. In reality it is likely that multiple infectious individuals were introduced into the UK at a later date. This distinction is immaterial to the functioning of the model. By calibrating to the mortality data, we obtain a transmission probability β of 0.0435 which translates to a basic reproduction number R_0 of 3.3 when *c* is 11 contacts per day and under no interventions. The results of the calibration are shown in Figure S1.

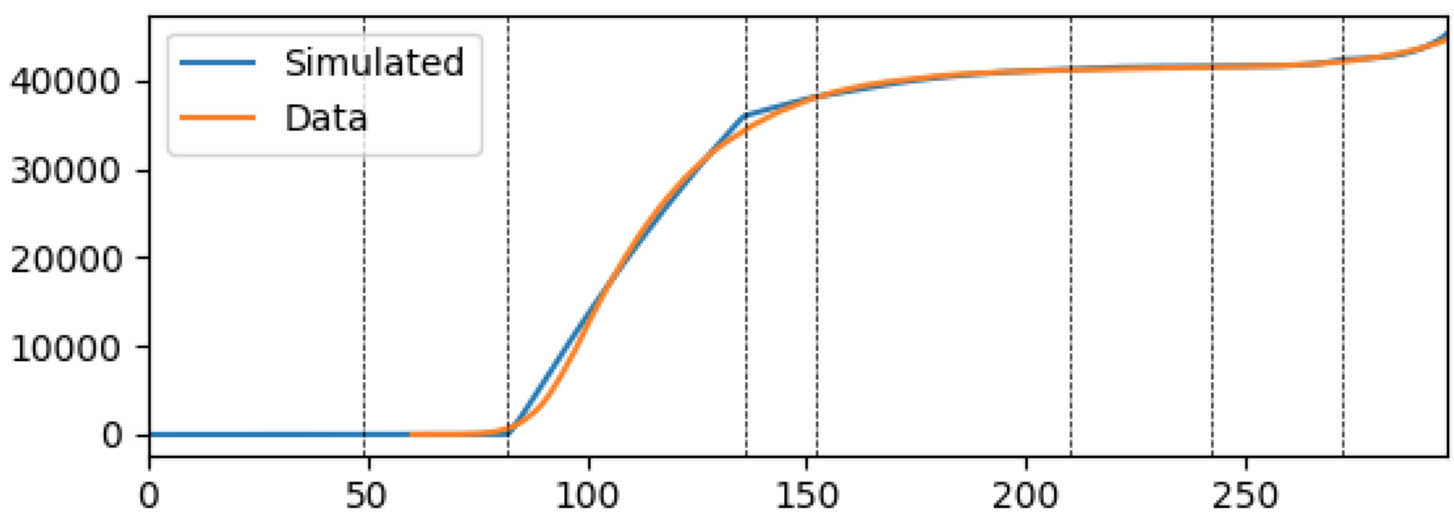

Figure S1: Results of the model calibration to deaths showing the excellent fit between model-predicted deaths and confirmed COVID-19 deaths from the UK data between 21/01/2020 and 23/10/2020.

Table S1: Model parameters

Parameter	**Description**	**Default Value***	**Reference**
N	Population size (UK population mid-year 2020)	67,886,011	[2]
c	Average contacts per day pre COVID-19	11	[3]
β (beta)	Transmission rate per contact	0.0435 on average but fitted across different time points in the epidemic	Estimated from fit to mortality data[4]
α^{-1} (alpha)	Incubation period (time from exposed to infectious)	5 days†	[5–8]
γ^{-1} (gamma)	Recovery period (time from infection to recovery or hospitalisation)	7 days†	[9,10]
κ^{-1} (kappa)	Isolation period (symptom free days)	14 days	[11]
θ (theta)	Testing rate of infectious individuals	Varied across scenarios	-
χ (chi)	Contact tracing rate		

η (eta)	Efficiency or success rate of contact tracing and isolation	0	-

Economic model

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

Contact tracing costs

Using our assumptions around number of contacts before lockdown (c0=11), during lockdown (c=0.3*c0), and after the lockdown is lifted (c=0.8*c0), we determine that over a period of 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 S4). We estimate the cost per contact traced is approximately £18 (calculations as per 'Tracing costs per case traced' sheet here).

Testing costs

We estimate that each test costs £4.79 including start-up and recurring costs. The vast majority of these costs are the £4.50 for each actual test (£3.50 for the test kit, £0.50 for mailing out the test kit, and £0.50 for the courier from the tested person's address to the local lab). Start-up costs for testing are the cost of the RT-LAMP machines (£27,000 each). Each machine can run 96 tests every 30 minutes[13] so if we assume they will be running for 18 hours per day (two nine-hour shifts) they will process 3,456 tests per day. We assume 10 machines per lab on average, each with £500 per day overheads, 40 lab workers (four per machine: two for each shift), and two supervisors (one for each shift).

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

Table S2: PTTI Resources Required

Shown are unit/daily costs. Total costs are variable dependent on policy scenario and case numbers.

1. Contact tracing

Staff	Function	Number	Rationale for number	Salary per day	Notes
Public Health Community Officer	Trace contacts via apps and in person - follow-up to check isolation and re-testing	81463	1 per 1000 population (like community health workers in many countries) + 20% for sickness cover and absence	£80	These workers can be people who have lost their employment as a result of the lockdown, they will need minimum qualifications though no prior experience of public health work as can be trained
Public Health COVID-19 supervisor	Supervisor / manager for PHCOs - ~1 per 50, or ~4 per each of the 343 local authority areas	1629	these team leads will work full time answering queries from PCHO and helping resolve problems + 20% for sickness cover and absence	£160	These supervisors could be recent graduates of public health or related Masters courses, or local authority Environmental Health Officers.
Local authority team lead	One for each of the 343 Local authorities	412	1 for overall control of contact tracing effort for each local authority area + 20% for sickness cover and absence	£300	These team leads should be public health specialists with at least 5 years experience
Online training for all staff		1	Three training courses (including refreshers) one for each staff cadre. Assume repeated every 3 months		generously funded at £20,000 per online training course developed (can do on phones which will be used for contact tracing too) + £500 per month for running servers for online training
				Unit cost	

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

Travel				Cost per day	
For supervisors and managers	to check work of PCHOs in person if needed	2,041	number of supervisors and managers	£10	Travel will be in local areas so costs per day for driving or public transport should not be high
For PCHO in rural areas	to get around to their whole catchment population of 1000 people	13,849	17% of UK population is rural so have this travel allowance for 17% of PCHO	£10	Travel will be in local areas so costs per day for driving or public transport should not be high
3 MONTH PERIOD COST: Communications	To advertise the contact tracing scheme and keep people informed of it	1	Estimated budget of £100,000 per day for advertising and communications. Advertising campaigns assumed to last for a minimum of 3 months	£9,125,000	This will be additional to national COVID-19 advertising budgets given current on-going COVID-19 advertising campaigns funded by the government

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

Staff	Function	Number	Rationale for number	Salary per day	Notes

Lab technicians	running SARS-Cov-2 viral RNA RT LAMP tests	11,574	18 hrs per day, two 9 hrs shifts: 1 technician running one machine, and 1 filling the wells per machine. So 4 shifts per day. Automated reporting into LMIS system - electronic connection into health records automatically.	£200	
Lab supervisors	supervising lab	579	two one for each lab (one for each 9hr shift) - average 10 RT LAMP machines per lab	£300	
Lab staff training	training on running RT LAMP tests	12,153	Initial 2 day training, 1 day refresher every 3 months	£200	5 days training per year
				unit cost	
Recruitment costs	Recruitment costs for all lab staff, including for replacements and cover	12153	£200 per recruitment for advertisements, phone interviews, salary of recruiters	£200	
Overheads					
Lab overheads	Overhead (space) costs for ordinary laboratory with category 2 hood (no biosecurity)	579	Estimated cost of £500 per day per lab for 289 labs with 10 RT LAMP machines in each	£500	
Machines				**RT LAMP machine cost per day**	

START-UP COSTS: RT LAMP Machines	SARS-Cov-2 viral RNA RT LAMP testing. Also automatically uploads data to online health records	2,894	Enough RT LAMP machines for 10 million tests a day if running 6 days a week 18 hrs a day, one 96 well plate per 30 minutes (20 min start to finish and 10 min turn around per run). One RT LAMP machine costs £27,000. Having this as an annual cost assumes all machines will be replaced after 12 months on average	£214,041	Total cost per year based on daily cost. If extending time beyond one year can use this as it is based on daily cost i.e. assumes RT LAMP machine lasts for 1 year or average and will then be replaced
RT LAMP Machine maintenance	maintain working order of the 2894 RT LAMP machines used	2,894	assume maintenance costs averaging £10 per day	£28,935	
Equipment				**Unit cost**	
Test kits, including reagents	viral RNA RT LAMP tests, home saliva samples. RT LAMP is at room temperature and doesn't require RNA extraction, so less reagents needed	3,120,000,000	10 million tests per day	£3.50	Reagents and materials per test - commercially sensitive source - used for pilot study* costing
Home collection of saliva samples	To collect saliva samples by courier to the lab for testing	3,120,000,000	10 million tests per day[14]	£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.[15]

Cost of face coverings

We assume that if people are unable to afford their own face coverings they will be wearing reusable face coverings made from materials to hand in the home, at little or no cost. The UK government has 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 S3 shows potential health and social costs of lockdown that are not included in our economic model.

Table S3 Potential Health and Social Impacts of COVID-19 lockdown and impact on NHS of COVID-19 demand[16]

Sector			Processes affected	Potential adverse health outcome
NHS	Programmes	Screening across the lifecourse, e.g. neonatal, cancer	Delivery, uptake and action[17,18]	Avoidable morbidity and mortality
		Immunisation	Reduced uptake[19]	Reduced herd immunity Increase in vaccine preventable infection
	Child and adolescent health		Health visitor checks and support for parents Adolescent mental health[20] 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[21]	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[22]
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[23] Disrupted support services during lockdown Removal of temporary housing at the end of COVID-19	Poorer health outcomes
	Dementia	Isolation, less carer support[24] Harms e.g. falls	Poorer quality of life Higher morbidity and mortality

	Patients with disability	Access to services for complex medical needs[25] 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[26] 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[27] 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[28] 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 quality of life – 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 relatives of COVID-19 patients - 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[29] Increased rates of depression[29] Increased rates of condition related anxiety (COVID patients)[29]	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[27]				

Realising the Resources for different test-trace strategies

1. Contact tracing

There is emerging evidence that mobile phone contact tracing apps have the potential to facilitate effective COVID-19 epidemic control at scale and at speed.[30] Nevertheless, personal follow-up on foot will also be required to ensure all contacts, including the most vulnerable, are reached.[31] 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.[32,33] 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.[34]

Case finding and contact tracing

Contact tracing remains a key control measure for maintaining suppression of case counts.[35] Table S4 shows the staff needed to handle new cases and control spread through contact tracing and isolation.[36]

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 S4. 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 S4 will be required by them.

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

Contact tracing resources required for each new case	Public Health Community Officer (PCHO) hours
Interview new case and create list of contacts (45 min - 1hr)	0.85
Interview 14 high-risk* contacts (20 min each)	4.6
Interview 16 low-risk† contacts (10 min each)	2.7
Monitor 14 high-risk contacts daily for 10 days (10 min per call)	23.3
Monitor 16 low-risk contacts for 10 days (1 min per call)	2.7
Arrange to test symptomatic contacts (a) (10 minutes)	0.6
Car service taking 1 hour to test 50% of symptomatic contacts	3.1
Total hours	**37.8**
(a) Assume 3.7 symptomatic contacts per new case (URTI prevalence of 42/1000[37] and R_0 of 2.5[38])	

*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.[39]

†**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.[39]

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[36] (these numbers 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[40] 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 S2) 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.[41] Most local authorities have established volunteer registers[42] 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.

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.[43] 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,[44,45] which has been affirmed by evidence from previous epidemics including HIV[46,47] and Ebola.[48] Community-led and co-production approaches in the context of the COVID-19 response have been lacking,[49] 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.[50] 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[51,52] and can have positive knock on effects for mental health outcomes in the general population, which is a growing concern in the crisis.[53]

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[54] 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"[55] can be dealt with using the strategy developed by the ONS.

2. New 96-well machines running direct RT LAMP assays[56] 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 1).

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:
    1. Lab staff would wear PPE where necessary but would not be accredited to conduct medical tests.
    2. Laboratories would be advised on precautions but not accredited for handling infectious samples.
    3. LAMP reagent production with normal non-medical quality control cannot be hampered by patents or regulations on medical test manufacture.

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

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

These pilot studies, one of which has started on a smaller scale in Southampton with 14,000 people,[15] will show whether PTTI is a practicable way of responding to the COVID-19 epidemic. Even if the epidemic is not completely controlled in pilot studies the establishment of far greater testing and tracing capacity will facilitate other initiatives. Different households would return samples on different days, giving a daily sample of each small area. Depending on the proportion of people tested and cases detected a local outbreak could therefore be detected soon after it occurs, as test results would be automatically uploaded online by each LAMP machine.

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

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

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

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

One of the key bottlenecks for ramping up testing to such a large scale is the availability of reagents and test kit supplies for the tests. Creative ways of resolving this issue are urgently needed (Box 1).

Box 1: 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.[57,58] The UK government's five-pillar plan for scaling up COVID-19 testing[59] reaches out to local manufacturers to ramp up testing capability and pharmaceutical companies are also offering to help.[60] The extent to which such capacity can be transformed into sustained delivery of the government's current target of 500,000 swab and antibody tests per day is still unclear.

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.[61] 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[62] (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.[63] 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.[63]

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[64]).

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