Optimal adaptive control policies – an epidemiological/economic perspective

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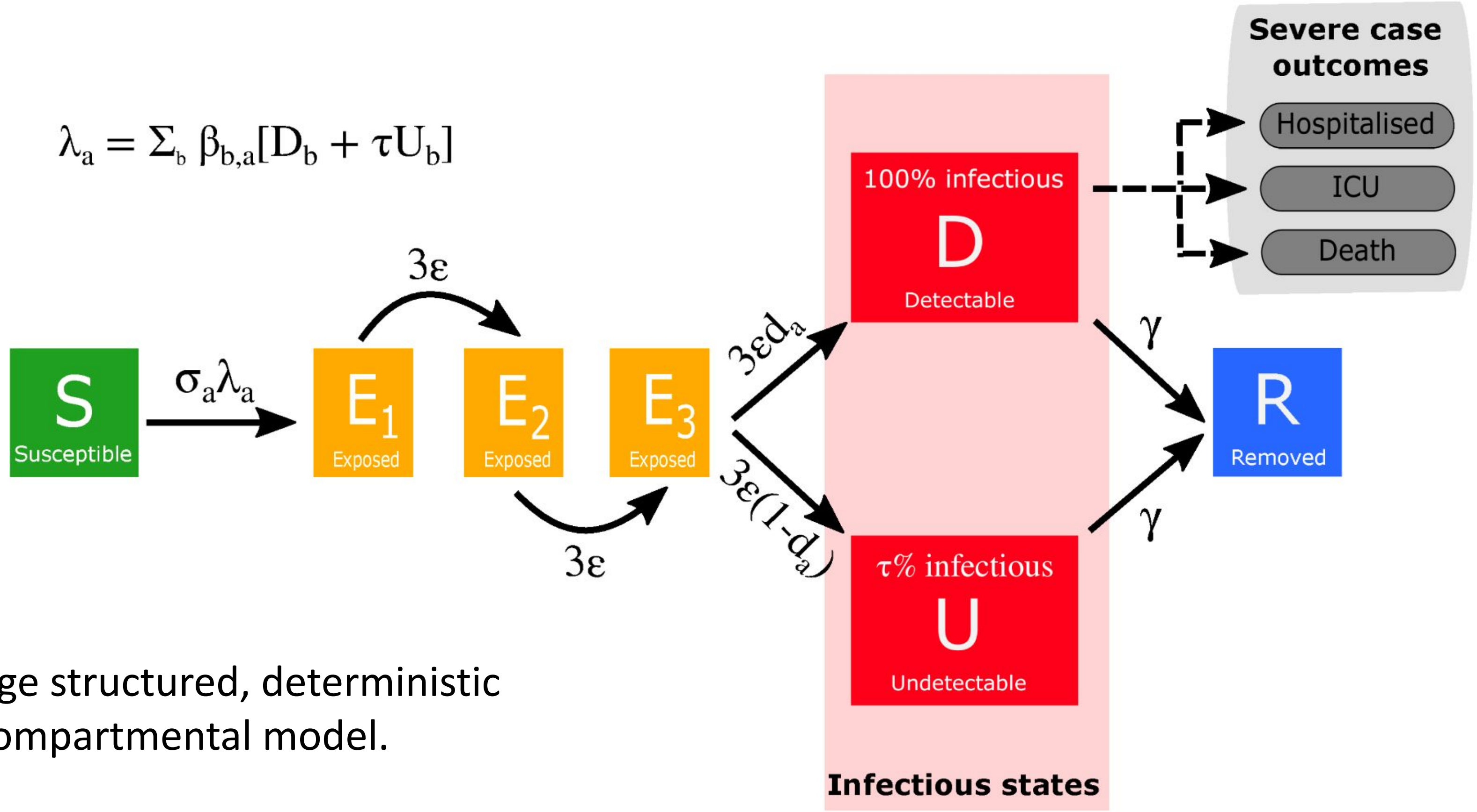
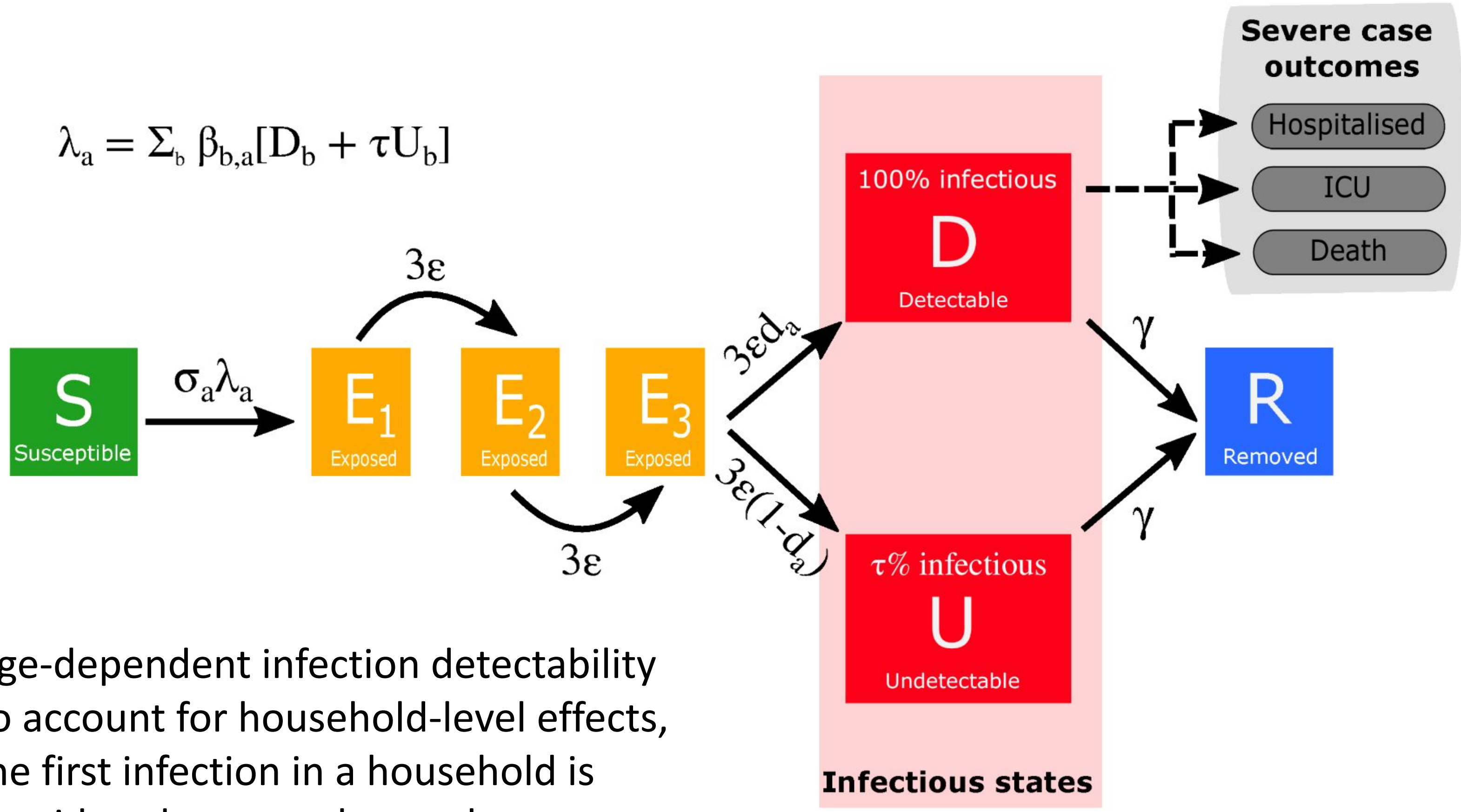
Modelling SARS-CoV-2 transmission: Disease state schematic



- Age structured, deterministic compartmental model.

Additional layers of complexity

$$\lambda_a = \Sigma_b\, \beta_{b,a}[D_b + \tau U_b]$$



- Age-dependent infection detectability
- To account for household-level effects, the first infection in a household is considered separately to subsequent infections.
- Includes household quarantine states

The equations

$$
\begin{aligned}
\frac{dS_a}{dt} &= -\left(\lambda_a^F + \lambda_a^{SD} + \lambda_a^{SU} + \lambda_a^Q\right)\frac{S_a}{N_a},\\
\frac{dE_a^F}{dt} &= \lambda_a^F \frac{S_a}{N_a} - \epsilon E_a^F,\\
\frac{dE_a^{SD}}{dt} &= \lambda^{SD} \frac{S_a}{N_a} - \epsilon E_a^{SD},\\
\frac{dE_a^{SU}}{dt} &= \lambda^{SU} \frac{S_a}{N_a} - \epsilon E_a^{SU},\\
\frac{dE_a^Q}{dt} &= \lambda^Q S - \epsilon E_a^Q,\\
\frac{dD_a^F}{dt} &= d_a(1-H)\epsilon E_a^F - \gamma D_a^F,\\
\frac{dD_a^{SD}}{dt} &= d_a \epsilon E_a^{SD} - \gamma D_a^{SD},\\
\frac{dD_a^{SU}}{dt} &= d_a(1-H)\epsilon E_a^{SU} - \gamma D_a^{SU},\\
\frac{dD_a^{QF}}{dt} &= d_a H \epsilon E_a^F - \gamma D_a^{QF},\\
\frac{dD_a^{QS}}{dt} &= d_a H \epsilon E_a^{SU} + d_a \epsilon E_a^Q - \gamma D_a^{QS},\\
\frac{dU_a^F}{dt} &= (1-d_a)\epsilon E_a^F - \gamma U_a^F,\\
\frac{dU_a^S}{dt} &= (1-d_a)\epsilon (E_a^{SD} + E_a^{SU}) - \gamma U_a^S,\\
\frac{dU_a^Q}{dt} &= (1-d_a)\epsilon E_a^Q - \gamma U_a^Q,
\end{aligned}
$$

A large set of ODE equations are used to describe the disease dynamics!

$$
\begin{aligned}
\lambda_a^F &= \sigma_a \sum_b \left(D_b^F + D_b^{SD} + D_b^{SU} + \tau(U_b^F + U_b^S)\right)\beta_{ba}^N,\\
\lambda_a^{SD} &= \sigma_a \sum_b D_b^F \beta_{ba}^H,\\
\lambda_a^{SU} &= \sigma_a \tau \sum_b U_a^F \beta_{ba}^H,\\
\lambda_a^Q &= \sigma_a \sum_b D_b^{QF} \beta_{ba}^H,
\end{aligned}
$$

The equations

Let’s zoom in on how the model simulates new infection:

Change in susceptibles of age a:

New infections reduce the number of susceptible people in the population

$$\frac{dS_a}{dt} = -\underbrace{\left(\lambda_a^F + \lambda_a^{SD} + \lambda_a^{SU} + \lambda_a^Q\right)}\frac{S_a}{N_a},$$

The “force of infection” depends on how many infectious people are in the population and their contact with the susceptible population

Depends on the proportion of people still susceptible

The equations

Let's zoom in on how the model simulates new infection:

Change in susceptibles of age a:

$$\frac{dS_a}{dt} = -\left(\lambda_a^F + \lambda_a^{SD} + \lambda_a^{SU} + \lambda_a^Q\right) \frac{S_a}{N_a},$$

$$\lambda_a^F = \sigma_a \sum_b \left(\underbrace{D_b^F + D_b^{SD} + D_b^{SU}}_{\text{"Detectable" infected people}} + \tau \underbrace{(U_b^F + U_b^S)}_{\text{"Undetectable" infected people}}\right) \beta_{ba}^N,$$

This "force of infection" term describes how people get infected from others not in their household

Age-dependent suspectibility

"Detectable" infected people

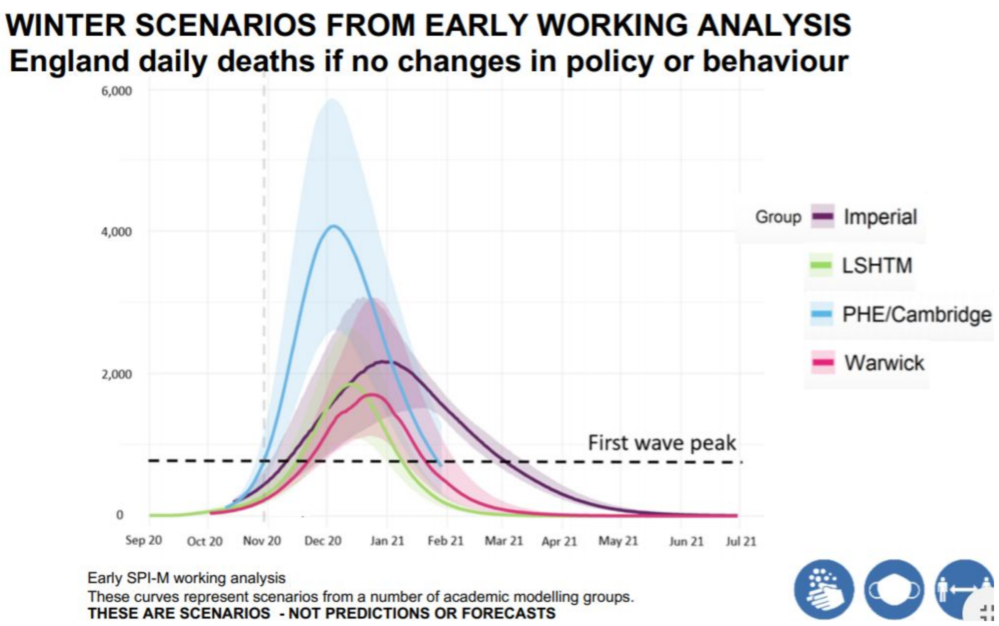
"Undetectable" infected people

Contact between different age groups

Forecasting and projections

The ODE model has been used for

- **R estimates and short-term forecasting**
- **Medium-term projections**
- **Longer term scenarios**
  - Reasonable worst case scenario
  - Vaccination



Circuit Breakers

- A "circuit breaker" is a short-term, planned lockdown
- It is intended to have a less severe effect on the economy, because it is planned

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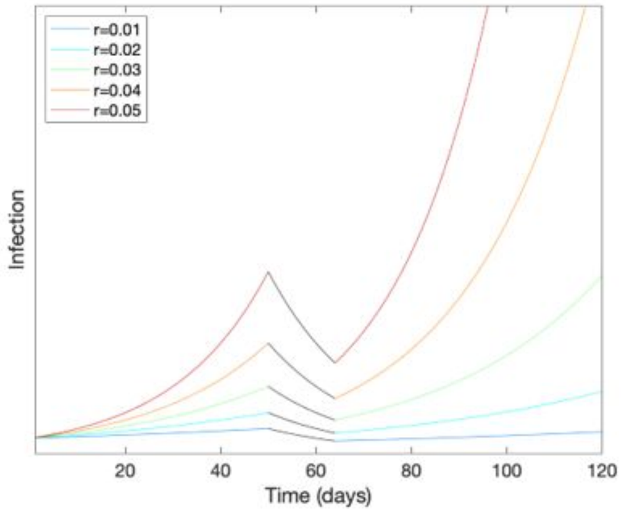
- A “circuit breaker” is a short-term, planned lockdown
- It is intended to have a less severe effect on the economy, because it is planned
- It does not “fix everything”!

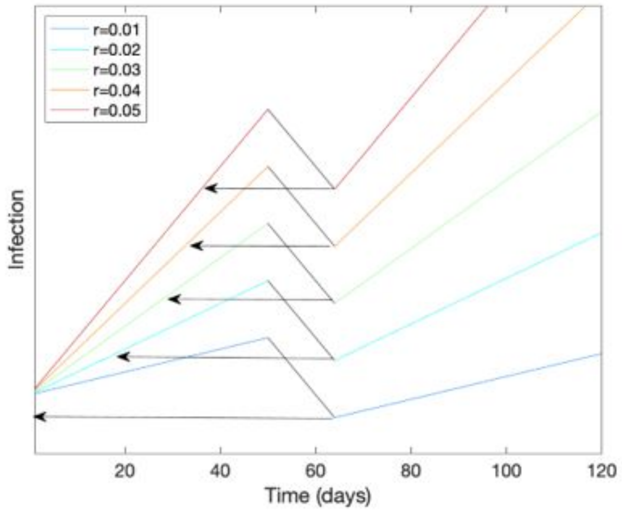
Simple Analytics

The action of a circuit breaker can be calculated analytically if the dynamics approximate exponential growth and decay. For an exponentially growing outbreak (rate r) and exponentially declining infection during the circuit breaker (rate $-s$), the dynamics can be approximated as:

$$Cases(t) = \begin{cases} A_1 \exp(rt) & t < Half\ Term \\ A_2 \exp(-st) & t \in Half\ Term \\ A_3 \exp(rt) & t > Half\ Term \end{cases}$$

where the parameters A_1, A_2 and A_3 are chosen to insure the cases are continuous.

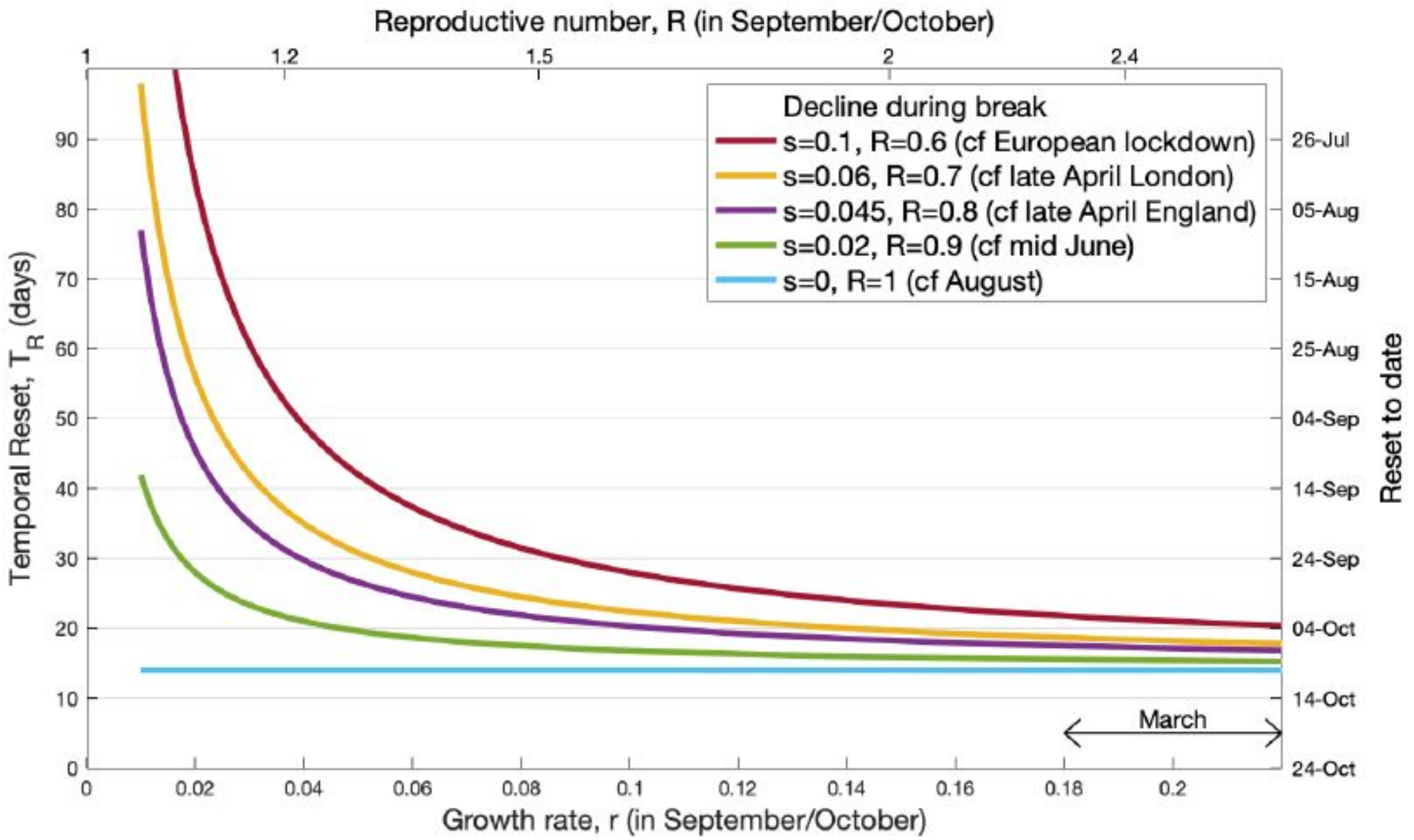




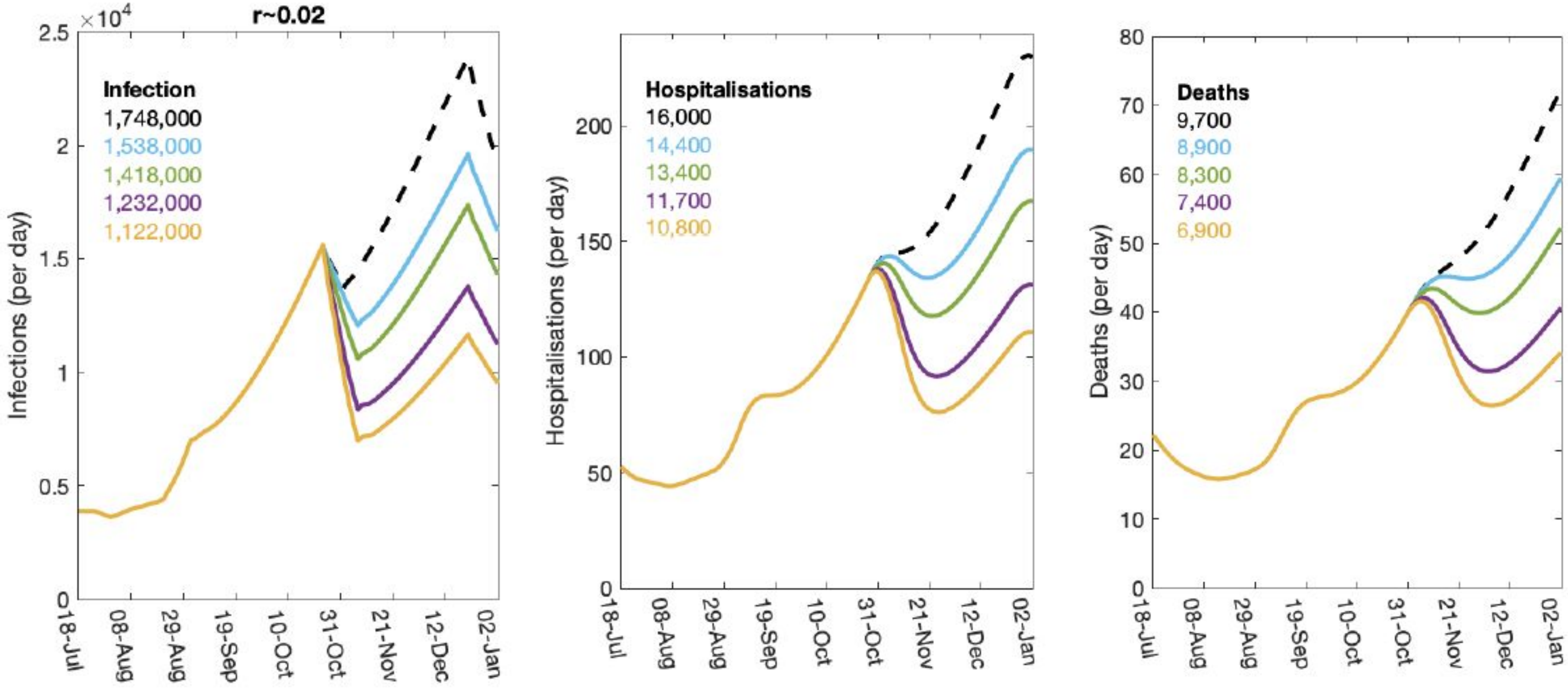
As shown in the two examples above, the action of any circuit-breaker over half term is to reduce the number of cases and effectively resets the number of cases to those at an earlier time. The duration of this "temporal reset" can be estimated from the simple approximation:

$$Temporal\ Reset = 14\left(1 + \frac{s}{r}\right)$$

Impact of a 2-week circuit breaker during half-term



Impact of a 2-week circuit breaker during half-term

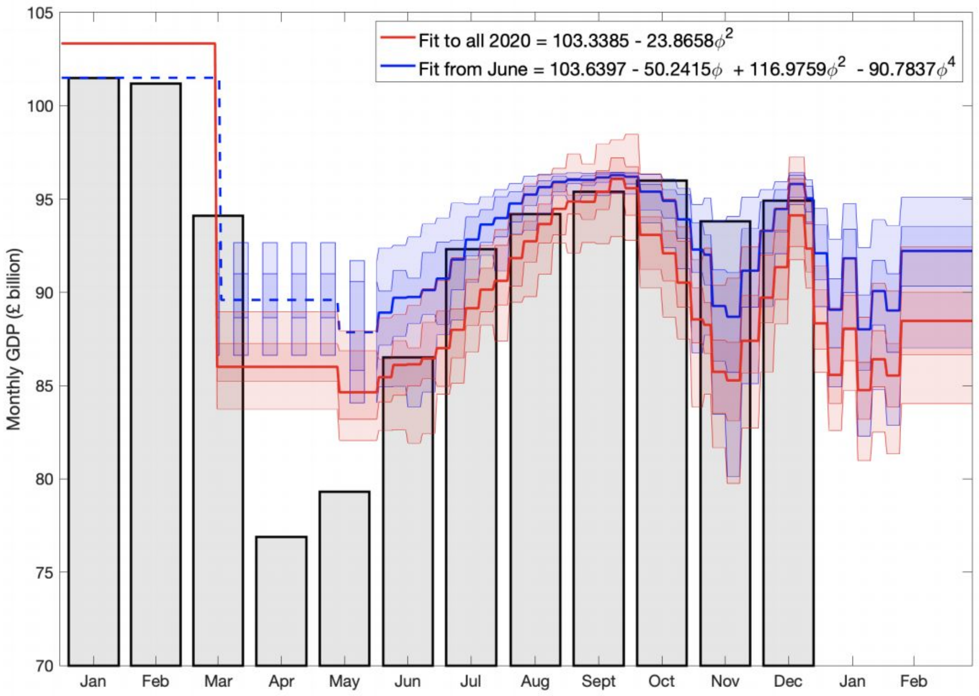


dashed black, no-control; blue s = 0; green s = 0:02; purple s = 0:045; gold s = 0:06

In much of the work presented to date, we have analysed policies based purely upon direct losses from COVID (cases/hospital admissions/deaths).

However, it is important to consider direct losses from COVID and economic losses as a result of lockdown.

We fit a model to monthly GDP, using parameter
$\emptyset$ as a measure of the intensity of control.



Given the potential "shock" in GDP as a result of the first lockdown, we investigate the impact of fitting to all 2020 and from June to December 2020.

We determine optimal lockdown policies based upon a given Willingness to Pay (W) per QALY loss avoided".

We aim to minimize W x QALY Loss + GDP loss.

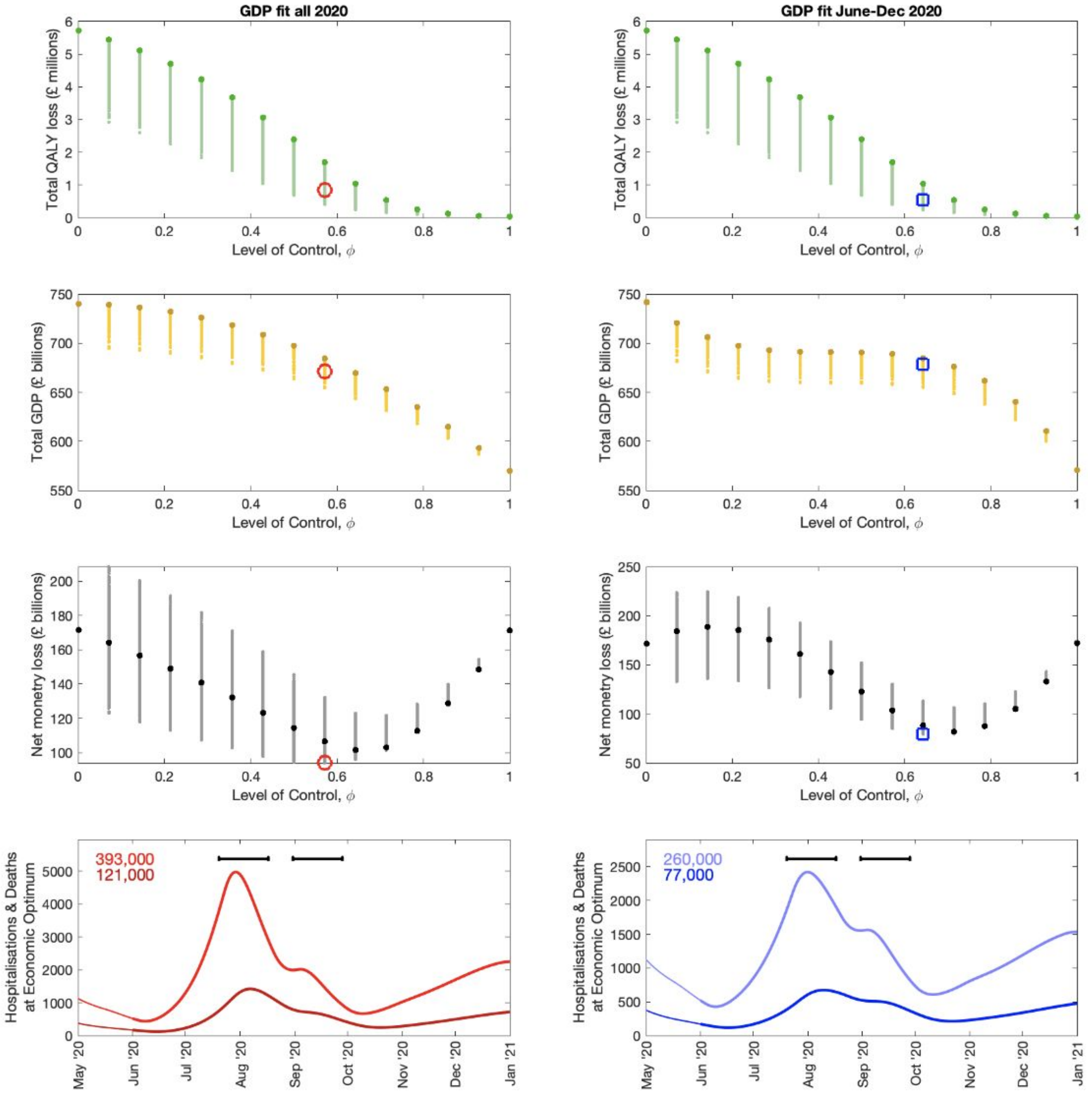
Evaluating the optimal control policy

We utilize our epidemiological model to carry out a series of simulations, varying the timing, frequency and intensity of lockdowns.

Based upon a given Willingness to Pay, we can establish the optimal strategy that should be implemented to minimize overall loss.

We also investigate the impact of imposing a threshold on hospital occupancy, in order to prevent the health service from being overwhelmed.

Willingness to Pay = £30,000 per QALY

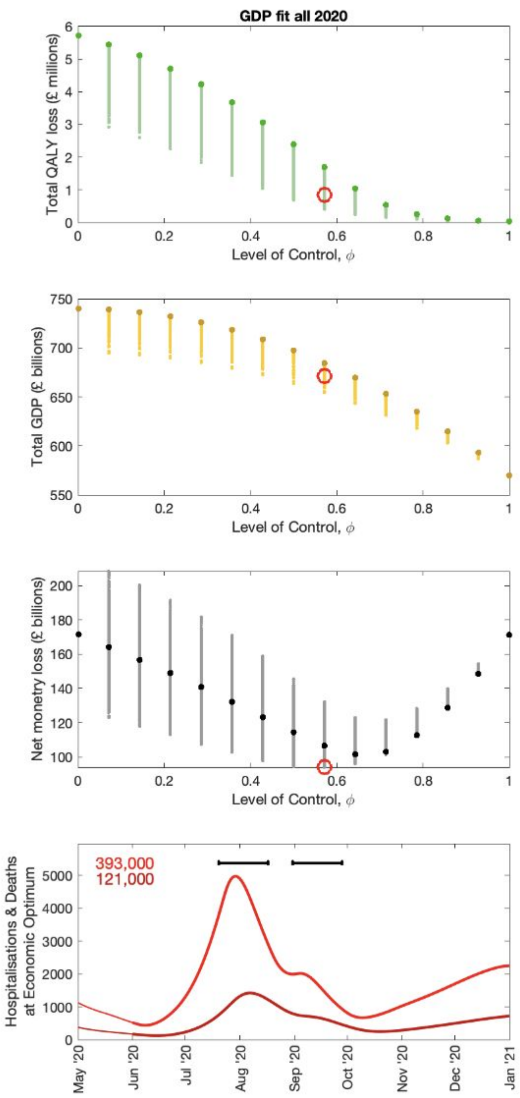


Dark circles correspond to constant level of control (outside circuit breaker).

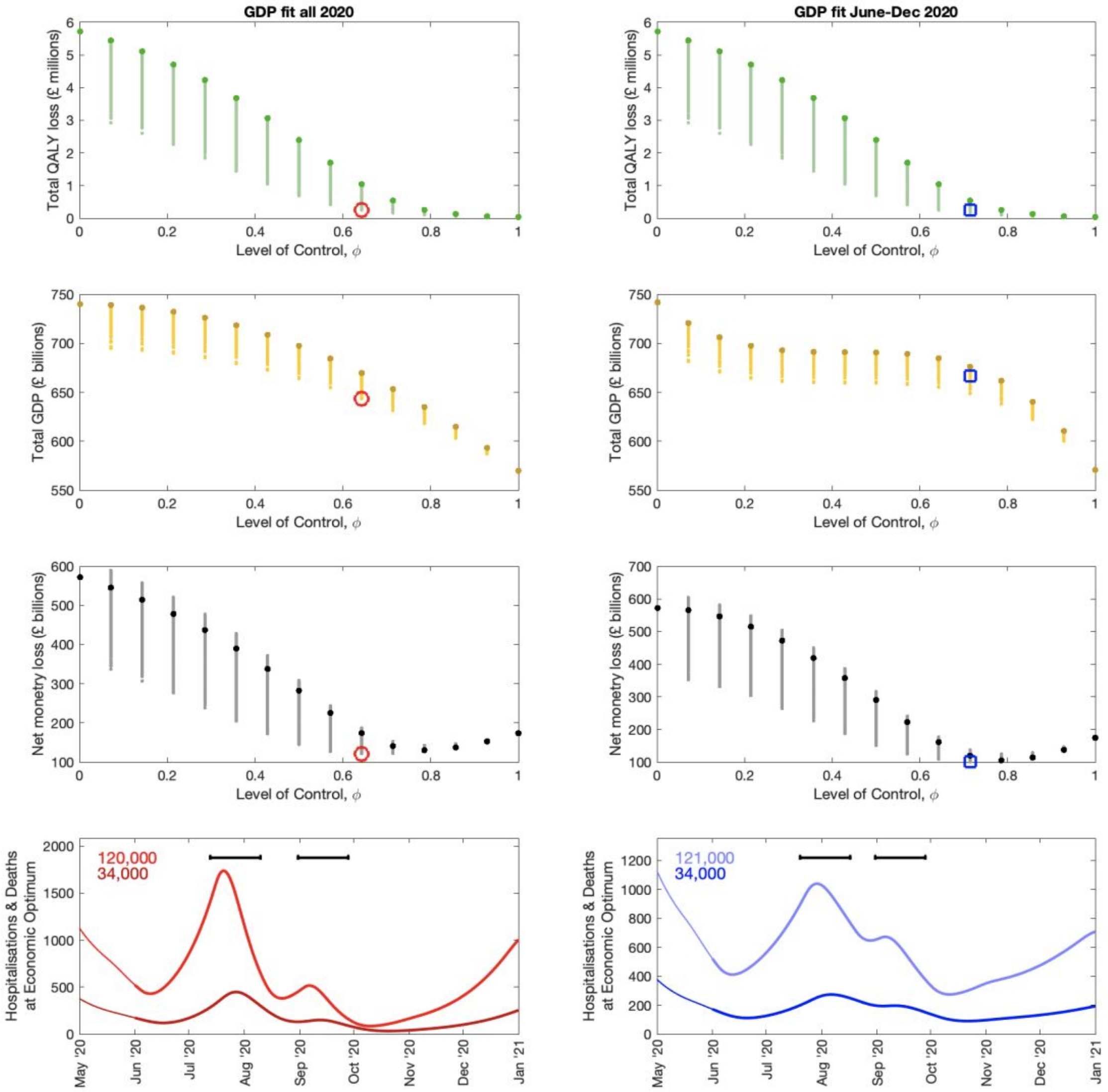
Smaller, paler dots correspond to different timings and intensities of circuit breakers.

Red/blue circles show policy that minimizes overall monetary loss.

Willingness to Pay = £30,000 per QALY

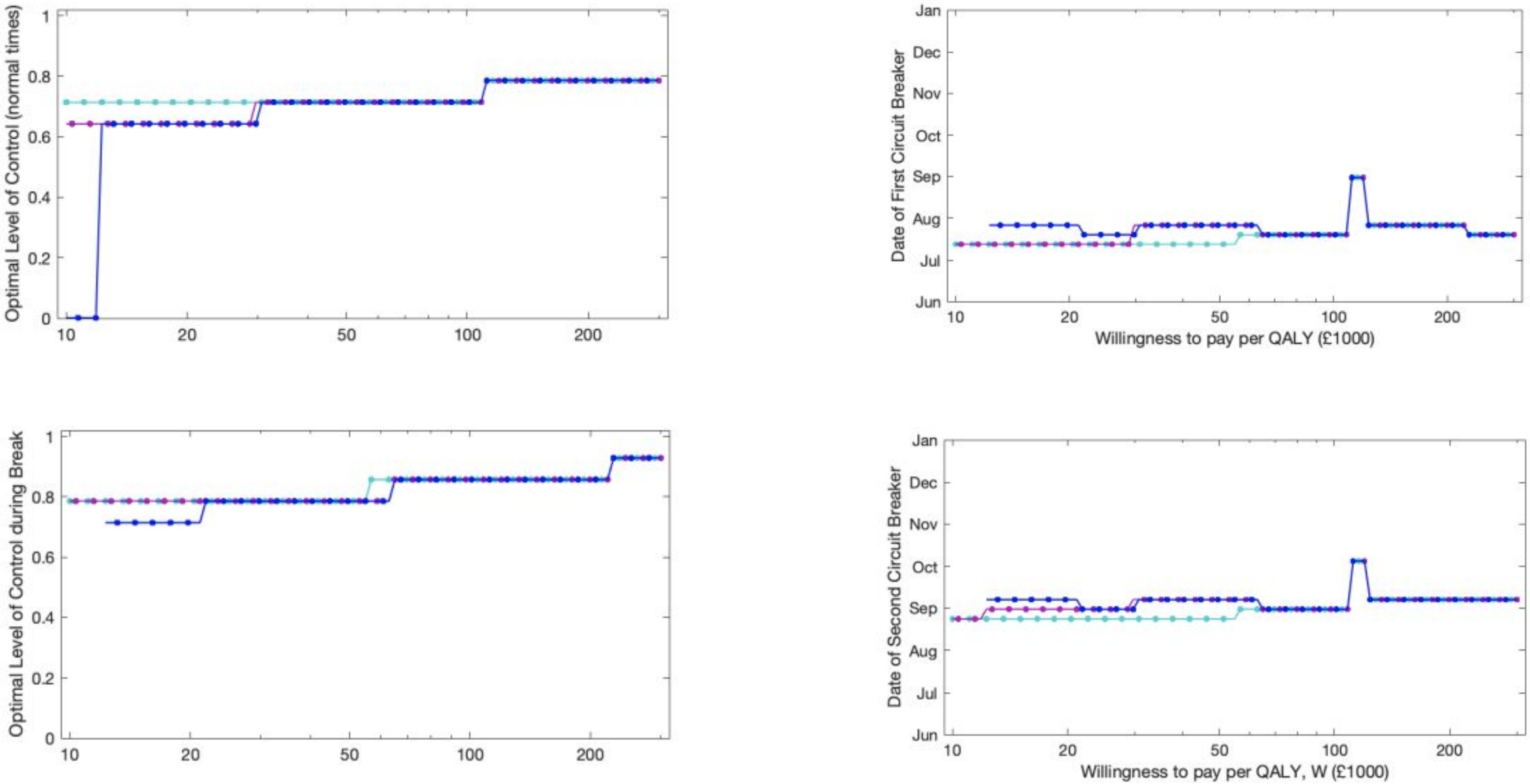


Willingness to Pay = £100,000 per QALY



We can see that the optimal level of control is dependent upon the value of W.

Optimal Policies Dependent upon Willingness to Pay



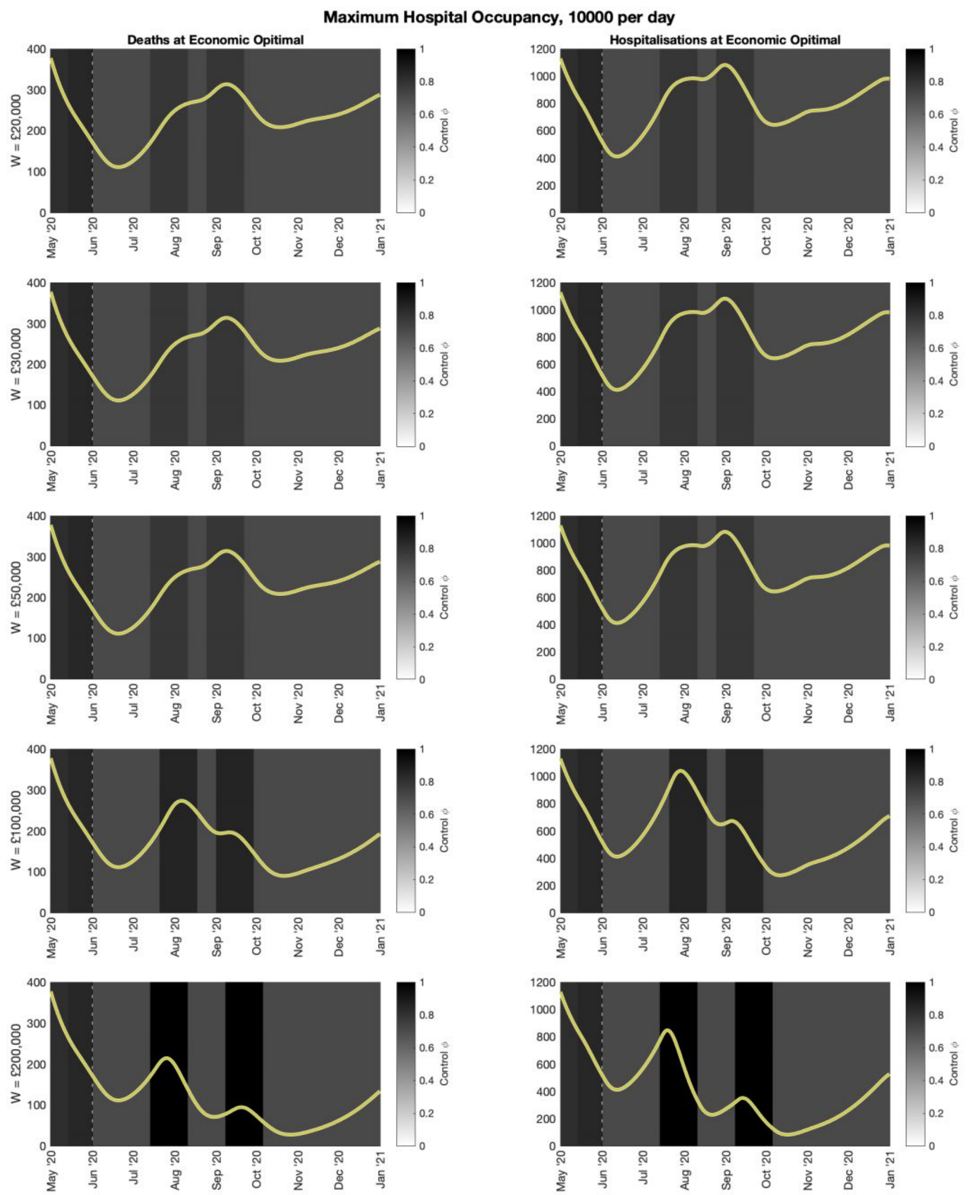
Willingness to Pay per QALY (£1000)

Optimal Policies Dependent upon Willingness to Pay

For a given value of W, we can therefore establish the optimal timing and intensity of lockdowns.

In these graphs, the background shading indicates the intensity of control both within and outside lockdown periods.

As the value of W increases, the intensity of control within and outside the circuit breakers increases at the optimal solution.

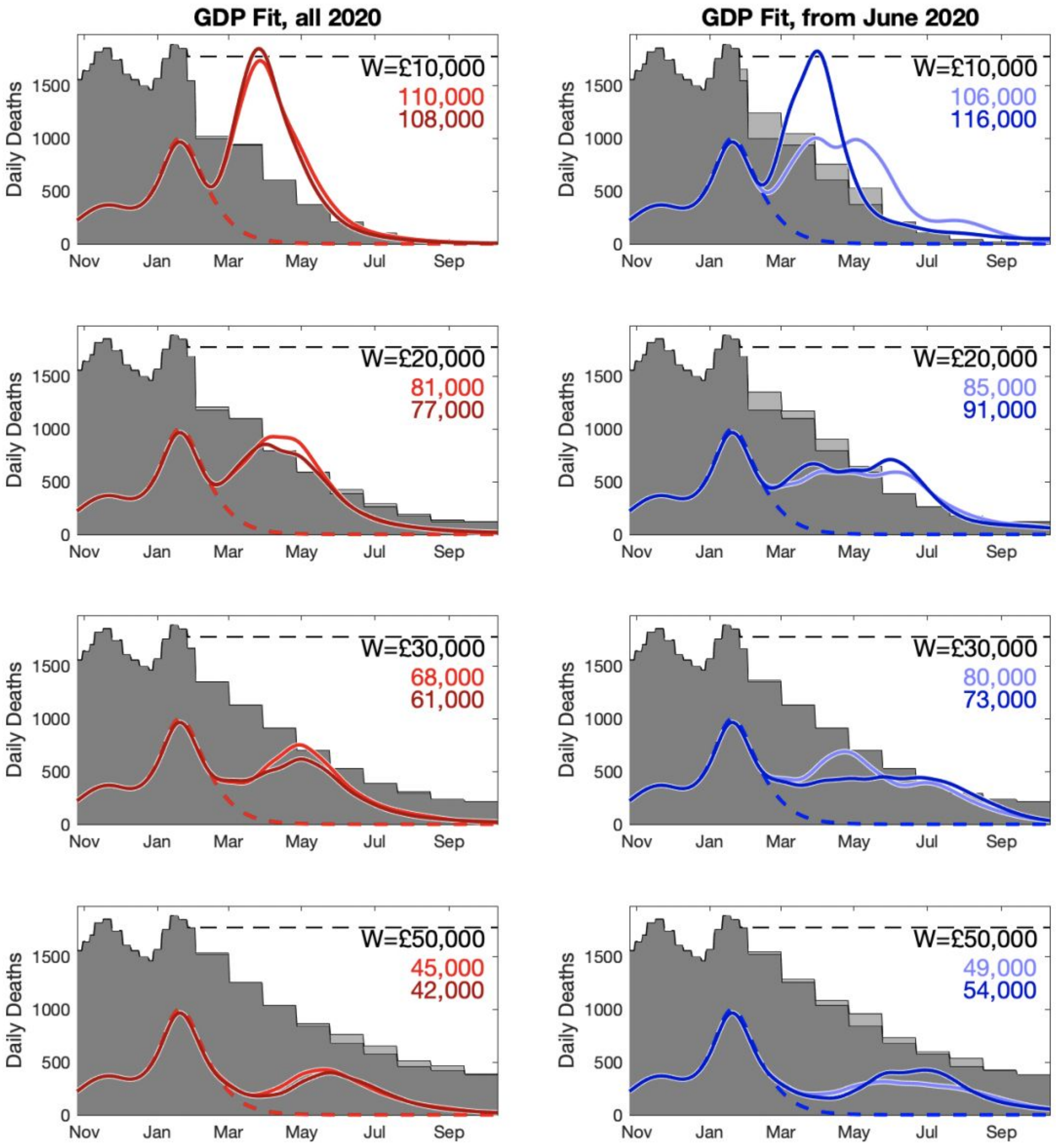


Optimal policy for relaxation of current lockdown in the presence of vaccination

We have also used our model to establish the optimal pace of relaxation of lockdown, based upon a given value of W.

We assume either 2 million or 4 million individuals can be vaccinated per week and compare with a strategy where lockdown remains in place throughout (dashed lines).

If W is high, the model predicts the optimal policy is a slow relaxation, which results in only a small resurgence in deaths.



Summary

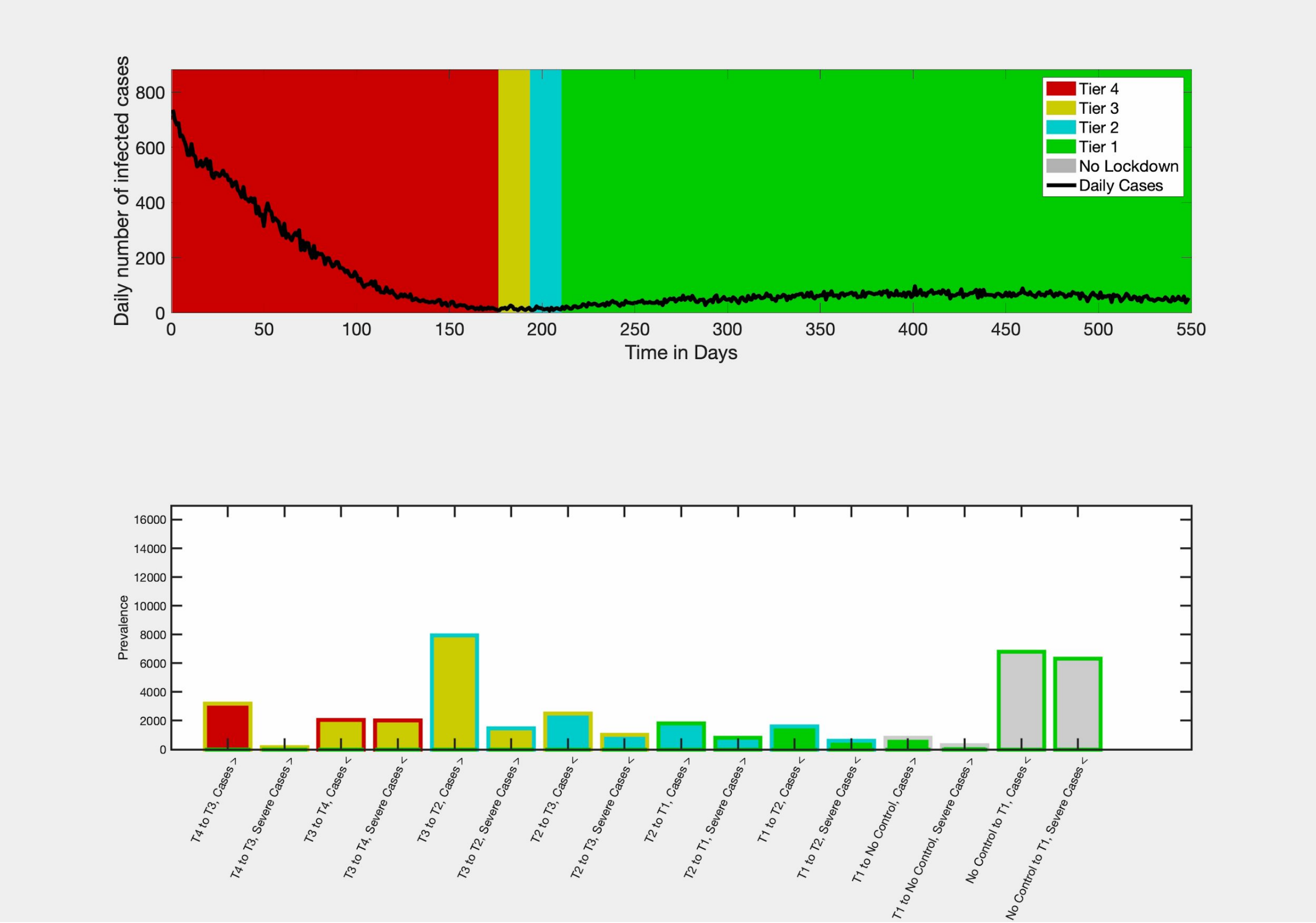
Our model indicates that the optimal policy for lockdowns is highly dependent upon the willingness to pay per QALY loss avoided.

We note that we have only used GDP as a measure for economic impact and other measures may be need to be incorporated (e.g. unemployment) to properly establish economic harm.

We are not directly considering health impacts of lockdown – only direct impacts of COVID are included in our QALY calculations.

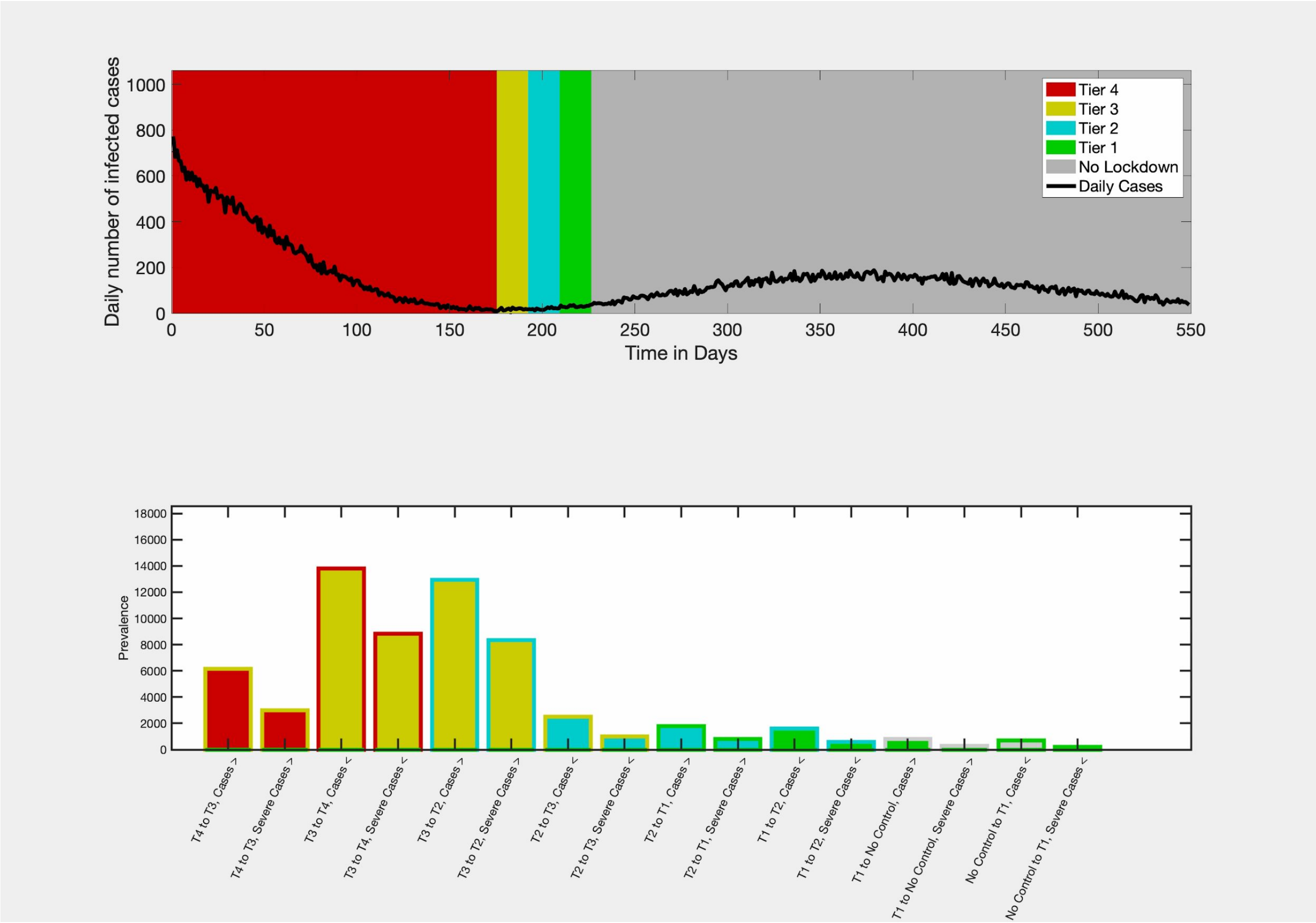
However, we have demonstrated the potential for epidemiological models to determine optimal control policies that take into account economic as well as epidemiological impact.

If we focus purely on COVID-health…



Optimal policy is for severe lockdown to be in place for a long time.

If we take more of an economic perspective…



Optimal policy results in rapid relaxation of control but causes a significant second wave.