Estimating and Simulating a SIRD Model of COVID-19 for Many Countries, States, and Cities

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Extended results for London, U.K.
Based on data through October 9, 2020
Outline of Slides

• Basic data from Johns Hopkins CSSE (raw and smoothed)
• Brief summary of the model
• Baseline results ($\delta = 1.0\%, \gamma = 0.2, \theta = 0.1$)
• Simulation of re-opening – possibilities for raising $R_0$
• Results with alternative parameter values:
  o Lower mortality rate, $\delta = 0.8\%$
  o Higher mortality rate, $\delta = 1.2\%$
  o Infections last longer, $\gamma = 0.15$
  o Cases resolve more quickly, $\theta = 0.2$
  o Cases resolve more slowly, $\theta = 0.07$
• Data underlying estimates of $R_0(t)$
Underlying data from Johns Hopkins CSSE

- Raw data
- Smoothed = 7 day centered moving average
- No “excess deaths” correction (change as of Aug 6 run)
London, U.K.: Daily Deaths per Million People

London, U.K.
London, U.K.: Daily Deaths per Million People (Smoothed)
**Brief Summary of Model**

- See the paper for a full exposition
- A 5-state SIRDC model with a time-varying $R_0$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$</td>
<td>1.0%</td>
<td>Mortality rate from infections (IFR)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.2</td>
<td>Rate at which people stop being infectious</td>
</tr>
<tr>
<td>$\theta$</td>
<td>0.1</td>
<td>Rate at which cases (post-infection) resolve</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.05</td>
<td>Rate at which $R_0(t)$ decays with daily deaths</td>
</tr>
<tr>
<td>$R_0$</td>
<td>...</td>
<td>Initial base reproduction rate</td>
</tr>
<tr>
<td>$R_0(t)$</td>
<td>...</td>
<td>Base reproduction rate at date $t$ ($\beta_t/\gamma$)</td>
</tr>
</tbody>
</table>
Estimates of Time-Varying $R_0$

– Inferred from daily deaths, and
– the change in daily deaths, and
– the change in (the change in daily deaths)
(see end of slide deck for this data)
London, U.K.: Estimates of $R_0(t)$

London, U.K.

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
London, U.K.: Percent Currently Infectious

London, U.K.

Peak I/N = 1.21%  Final I/N = 0.02%  δ = 0.010  θ = 0.10  γ = 0.20

Mar Apr May Jun Jul Aug Sep Oct
London, U.K.: Growth Rate of Daily Deaths over Past Week (percent)

\[
\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20
\]
Notes on Interpreting Results
Guide to Graphs

- **Warning:** Results are often very uncertain; this can be seen by comparing across multiple graphs. See the original paper.

- 7 days of forecasts: Rainbow color order!
  ROY-G-BIV (old to new, low to high)
  - Black = current
  - Red = oldest, Orange = second oldest, Yellow = third oldest...
  - Violet (purple) = one day earlier

- For robustness graphs, same idea
  - Black = baseline (e.g. $\delta = 1.0\%$)
  - Red = lowest parameter value (e.g. $\delta = 0.8\%$)
  - Green = highest parameter value (e.g. $\delta = 1.2\%$)
How does $R_0$ change over time?

- Inferred from death data when we have it

- For future, two approaches:
  
  1. Alternatively, we fit this equation:

     $\log R_0(t) = a_0 - \alpha(Daily\ Deaths)$

     $\Rightarrow \alpha \approx .05$

     $R_0$ declines by 5 percent for each new daily death, or rises by 5 percent when daily deaths decline

- Robustness: Assume $R_0(t) = $ final empirical value. Constant in future, so no $\alpha$ adjustment $\rightarrow \alpha = 0$
Repeated “Forecasts” from the past 7 days of data

– After peak, forecasts settle down.
– Before that, very noisy!
– If the region has not peaked, do not trust
– With $\alpha = .05$ (see robustness section for $\alpha = 0$)
London, U.K. (7 days): Daily Deaths per Million People ($\alpha = .05$)

London, U.K.

$R_0=2.1/1.1/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 7/7/7

DATA THROUGH 09-OCT-2020
London, U.K. (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

London, U.K.

$R_0=2.1/1.1/1.1 \ \delta = 0.010 \ \alpha=0.05 \ \theta=0.1 \ %\text{Infect}=7/7/7$

DATA THROUGH 09-OCT-2020
London, U.K. (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = ...$

London, U.K.

$R_0 = 2.1/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 7/7/7$
Robustness to Mortality Rate, $\delta$
London, U.K.: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

\begin{align*}
\text{London, U.K.} \\
R_0 &= 2.1/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 7/7/7
\end{align*}

DATA THROUGH 09-OCT-2020
London, U.K.: Daily Deaths per Million People ($\delta = .01/.008/.012$)

London, U.K.

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $%\text{Infect} = 7/7/7$

DATA THROUGH 09-OCT-2020
London, U.K.: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

London, U.K.

$R_0 = 2.1/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 7/7/7$

DATA THROUGH 09-OCT-2020
Reopening and Herd Immunity

– Black: assumes $R_0(\text{today})$ remains in place forever
– Red: assumes $R_0(\text{suppress}) = 1/s(\text{today})$
– Green: we move 25% of the way from $R_0(\text{today})$ back to initial $R_0 = \text{“normal”}$
– Purple: we move 50% of the way from $R_0(\text{today})$ back to initial $R_0 = \text{“normal”}$

NOTE: Lines often cover each other up
London, U.K.: Re-Opening ($\alpha = .05$)

London, U.K.

$R_0(t)=1.1, \ R_0(\text{suppress})=1.1, \ R_0(25/50)=1.4/1.6, \ \delta = 0.010, \ \alpha=0.05$

(Light bars = New York City, for comparison)
London, U.K.: Re-Opening ($\alpha = 0$)

London, U.K.

$R_0(t)=1.1$, $R_0(\text{suppress})=1.1$, $R_0(25/50)=1.4/1.6$, $\delta = 0.010$, $\alpha=0.00$

(Light bars = New York City, for comparison)
Results for alternative parameter values
London, U.K. (7 days): Daily Deaths per Million People ($\alpha = 0$)

London, U.K.

$R_0 = 2.1 / 1.1 / 1.1$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$ Infect $= 7 / 7 / 8$

DATA THROUGH 09-OCT-2020

[Graph showing daily deaths per million people in London, U.K. from April 2020 to February 2021]
London, U.K. (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

London, U.K.

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 7/7/8

DATA THROUGH 09-OCT-2020
London, U.K. (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

London, U.K.

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 7/7/8

New York City

Italy
London, U.K.: Daily Deaths per Million People ($\delta = 0.8\%$)

London, U.K.

$R_0=2.1/1.1/1.1$  $\delta = 0.008$  $\theta=0.1$  $\gamma=0.2$  $\%$Infect = 8/9/9
London, U.K.: Cumulative Deaths per Million ($\delta = 0.8\%$)

London, U.K.

$R_0 = 2.1/1.1/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%\text{Infect} = 8/9/9$
London, U.K.: Daily Deaths per Million People ($\delta = 1.2\%$)

London, U.K.
$R_0=2.1/1.1/1.1$ $\delta = 0.012$ $\theta=0.1$ $\gamma=0.2$ %Infect= 6/ 6/ 6
London, U.K.: Cumulative Deaths per Million (δ = 1.2\%)
London, U.K.: Daily Deaths per Million People ($\gamma = .2/.15$)

London, U.K.

$R_0 = 2.1/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}= 7/7/7$

DATA THROUGH 09-OCT-2020
London, U.K.: Cumulative Deaths per Million $\gamma = .2/.15$)

London, U.K.
$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  \%Infect $= 7/7/7$

DATA THROUGH 09-OCT-2020
London, U.K.: Daily Deaths per Million People ($\theta = 1/0.07/2$)

London, U.K.

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 7/7/7

DATA THROUGH 09-OCT-2020
London, U.K.: Cumulative Deaths per Million People ($\theta = .1 / .07 / .2$)

\[ R_0 = 2.1 / 1.1 / 1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 7 / 7 / 7 \]

DATA THROUGH 09-OCT-2020
Data Underlying Estimates of Time-Varying $R_0$

– Inferred from daily deaths, and
– the change in daily deaths, and
– the change in (the change in daily deaths)
London, U.K.: Daily Deaths, Actual and Smoothed

London, U.K.: Daily deaths, \(d\)
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
London, U.K.: Change in Smoothed Daily Deaths

London, U.K.: Delta \( d \)

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
London, U.K.: Change in (Change in Smoothed Daily Deaths)

London, U.K.: Delta (Delta d)

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]