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

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Extended results for United Kingdom
Based on data through August 24, 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:
  - Lower mortality rate, \( \delta = 0.8\% \)
  - Higher mortality rate, \( \delta = 1.2\% \)
  - Infections last longer, \( \gamma = 0.15 \)
  - Cases resolve more quickly, \( \theta = 0.2 \)
  - 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)
United Kingdom: Daily Deaths per Million People

United Kingdom
United Kingdom: 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)
United Kingdom: Estimates of $R_0(t)$

United Kingdom

$\delta = 0.010$  $\theta = 0.10$  $\gamma = 0.20$
United Kingdom: Percent Currently Infectious

United Kingdom
Peak I/N = 0.79%  Final I/N = 0.01%  δ = 0.010  θ = 0.10  γ = 0.20
United Kingdom: Growth Rate of Daily Deaths over Past Week (percent)

United Kingdom
\(\delta = 0.010 \quad \theta=0.10 \quad \gamma=0.20\)
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 $R_0(t) = \text{final empirical value}$. 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 $\alpha = 0$)
United Kingdom (7 days): Daily Deaths per Million People ($\alpha = .05$)

United Kingdom

$R_0 = 2.0/0.8/0.8$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 6/ 6/ 6

DATA THROUGH 21-AUG-2020
United Kingdom (7 days): Cumulative Deaths per Million (Future, $\alpha = 0.05$)

DATA THROUGH 24-AUG-2020

United Kingdom

$R_0 = 2.0/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6$
United Kingdom (7 days): Cumulative Deaths per Million, Log Scale

United Kingdom

$R_0 = 2.0/0.8/0.8$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 6/6/6

New York City

Italy
Robustness to Mortality Rate, $\delta$
United Kingdom: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

United Kingdom

$R_0=2.0/0.8/0.8$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%Infect= 6/6/6$

DATA THROUGH 24-AUG-2020
United Kingdom: Daily Deaths per Million People ($\delta = .01/.008/.012$)

United Kingdom

$R_0 = 2.0/0.8/0.8$  \( \delta = 0.010 \)  \( \alpha = 0.05 \)  \( \theta = 0.1 \)  \%Infect = 6/6/6

DATA THROUGH 23-AUG-2020
United Kingdom: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

United Kingdom

$R_0 = 2.0/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6$

Data through 24-Aug-2020
Reopening and Herd Immunity

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

NOTE: Lines often cover each other up
United Kingdom: Re-Opening ($\alpha = .05$)

United Kingdom

$R_0(t)=0.8, \ R_0(\text{suppress})=1.1, \ R_0(25/50)=1.1/1.4, \ \delta = 0.010, \ \alpha=0.05$
United Kingdom: Re-Opening ($\alpha = 0$)

United Kingdom

$R_0(t)=0.8$, $R_0(\text{suppress})=1.1$, $R_0(25/50)=1.1/1.4$, $\delta = 0.010$, $\alpha=0.00$
Results for alternative parameter values
United Kingdom (7 days): Daily Deaths per Million People ($\alpha = 0$)

United Kingdom

$R_0 = 2.0/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6$

DATA THROUGH 21-AUG-2020
United Kingdom (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

United Kingdom

$R_0 = 2.0/0.8/0.8$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 6/6/6

DATA THROUGH 24-AUG-2020
United Kingdom (7 days): Cumulative Deaths per Million, Log Scale

United Kingdom
\[ R_0 = 2.0/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6 \]
United Kingdom: Daily Deaths per Million People ($\delta = 0.8\%$)

United Kingdom

$R_0 = 2.0/0.8/0.9 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 8/8/8$
United Kingdom: Cumulative Deaths per Million ($\delta = 0.8\%$)

United Kingdom

$R_0=2.0/0.8/0.9 \quad \delta = 0.008 \quad \theta=0.1 \quad \gamma=0.2 \quad \%\text{Infect}= 8/8/8$
United Kingdom: Daily Deaths per Million People ($\delta = 1.2\%$)

United Kingdom

$R_0 = 2.0/0.8/0.8 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 5/5/5$
United Kingdom: Cumulative Deaths per Million ($\delta = 1.2\%$)

United Kingdom

$R_0 = 2.0/0.8/0.8 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 5/5/5$
United Kingdom: Daily Deaths per Million People ($\gamma = .2/.15$)

United Kingdom

$R_0=2.0/0.8/0.8 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=6/6/6$

DATA THROUGH 21-AUG-2020
United Kingdom: Cumulative Deaths per Million $\gamma = .2/.15$)

United Kingdom

$R_0=2.0/0.8/0.8 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%Infect= 6/6/6$

$\gamma = 0.25$

DATA THROUGH 24-AUG-2020
United Kingdom: Daily Deaths per Million People ($\theta = .1/.07/.2$)

United Kingdom

$R_0=2.0/0.8/0.8$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%\text{Infect}=6/6/6$

DATA THROUGH 21-AUG-2020
United Kingdom: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

United Kingdom

$R_0 = 2.0/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/6/6$

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people
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)
United Kingdom: Delta \( \delta \)
\( \delta = 0.010 \) \( \theta = 0.10 \) \( \gamma = 0.20 \)
United Kingdom: Change in (Change in Smoothed Daily Deaths)

United Kingdom: Delta (Delta d)
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]