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

Jesús Fernández-Villaverde and Chad Jones

Extended results for New Hampshire
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)
New Hampshire: Daily Deaths per Million People (Smoothed)

New Hampshire

Daily deaths per million people (smoothed)

Apr May Jun Jul Aug 2020

-6 -4 -2 0 2 4 6 8 10 12 14

2020
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)
New Hampshire: Estimates of $R_0(t)$

New Hampshire

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
New Hampshire: Percent Currently Infectious

Peak I/N = 0.34%  Final I/N = 0.03%  δ = 0.010  θ = 0.10  γ = 0.20
New Hampshire: 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:

\[
\log R_0(t) = a_0 - \alpha (\text{Daily Deaths})
\]

\[\Rightarrow \alpha \approx 0.05\]

$R_0$ 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 $\alpha = 0$)
New Hampshire (7 days): Daily Deaths per Million People ($\alpha = .05$)

**New Hampshire**

$R_0 = 1.8 / 1.3 / 1.1$  
$\delta = 0.010$  
$\alpha = 0.05$  
$\theta = 0.1$  
%Infect = 3/4/9

Data through 24-Aug-2020
New Hampshire (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

New Hampshire

$R_0 = 1.8/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect = 3/4/9

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

\[ R_0 = 1.8/1.3/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 3/4/9 \]
Robustness to Mortality Rate, $\delta$
New Hampshire: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

New Hampshire

$R_0=1.8/1.3/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 3/4/9

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

New Hampshire

$R_0 = 1.8/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 3/4/9

DATA THROUGH 24-AUG-2020

Daily deaths per million people
New Hampshire: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

New Hampshire

$R_0 = 1.8/1.3/1.1 \, \delta = 0.010 \, \alpha = 0.05 \, \theta = 0.1 \, \% \text{Infect} = 3/4/9$

DATA THROUGH 24-AUG-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 $R_0 =$ “normal”

– **Purple**: we move 50% of the way from $R_0(\text{today})$ back to initial $R_0 =$ “normal”

**NOTE**: Lines often cover each other up
New Hampshire: Re-Opening ($\alpha = .05$)

New Hampshire

$R_0(t)=1.3$, $R_0(\text{suppress})=1.0$, $R_0(25/50)=1.5/1.7$, $\delta = 0.010$, $\alpha=0.05$
New Hampshire: Re-Opening \((\alpha = 0)\)

\[ R_0(t) = 1.3, \quad R_0(\text{suppress}) = 1.0, \quad R_0(25/50) = 1.5/1.7, \quad \delta = 0.010, \quad \alpha = 0.00 \]
Results for alternative parameter values
New Hampshire (7 days): Daily Deaths per Million People ($\alpha = 0$)

New Hampshire

$R_0=1.8/1.3/1.3$  \(\delta = 0.010\)  \(\alpha=0.00\)  \(\theta=0.1\)  \%Infect= 3/ 4/37

DATA THROUGH 24-AUG-2020
New Hampshire (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

New Hampshire

$R_0 = 1.8/1.3/1.3 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%Infect= 3/4/37$

Data through 24-Aug-2020
New Hampshire (7 days): Cumulative Deaths per Million, Log Scale

\[ R_0 = 1.8/1.3/1.3 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 3/4/37 \]
New Hampshire: Daily Deaths per Million People ($\delta = 0.8\%$)

New Hampshire

$R_0 = 1.8/1.3/1.1$  \( \delta = 0.008 \)  \( \theta = 0.1 \)  \( \gamma = 0.2 \)  \%Infect = 4/5/11
New Hampshire: Cumulative Deaths per Million ($\delta = 0.8\%$)

New Hampshire

$R_0 = 1.8/1.3/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 4/5/11
New Hampshire: Daily Deaths per Million People ($\delta = 1.2\%$)

New Hampshire

$R_0 = 1.8/1.3/1.1 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 3/3/7$
New Hampshire: Cumulative Deaths per Million ($\delta = 1.2\%$)

New Hampshire

$R_0 = 1.8/1.3/1.1$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $% \text{Infect} = 3/3/7$
New Hampshire: Daily Deaths per Million People ($\gamma = .2/.15$)

New Hampshire

$R_0 = 1.8/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 3/4/9

DATA THROUGH 24-AUG-2020
New Hampshire: Cumulative Deaths per Million $\gamma = 0.2/0.15$)

New Hampshire

$R_0 = 1.8/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 3/4/9

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

New Hampshire

$R_0 = 1.8 / 1.3 / 1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 3 / 4 / 9$

DATA THROUGH 24-AUG-2020
New Hampshire: Cumulative Deaths per Million People ($\theta = .1 / .07 / .2$)

New Hampshire

$R_0 = 1.8 / 1.3 / 1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 3/4/9

DATA THROUGH 24-AUG-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)
New Hampshire: Daily Deaths, Actual and Smoothed

New Hampshire: Daily deaths, \( d \)

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
New Hampshire: Change in Smoothed Daily Deaths

New Hampshire: Delta $d$

$\delta = 0.010$  $\theta = 0.10$  $\gamma = 0.20$
New Hampshire: Change in (Change in Smoothed Daily Deaths)

New Hampshire: Delta (Delta d)

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