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

Jesús Fernández-Villaverde and Chad Jones

Extended results for Indiana
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:
  - 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)
Indiana: Daily Deaths per Million People

![Graph of Indiana's daily deaths per million people from April to October 2020. The x-axis represents the months from April to October, and the y-axis represents the daily deaths per million people. The graph shows fluctuations in daily deaths, with a significant increase in May.]
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)
Indiana: Estimates of $R_0(t)$

Indiana

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

Peak I/N = 0.37%   Final I/N = 0.12%   \( \delta = 0.010 \)   \( \theta = 0.10 \)   \( \gamma = 0.20 \)
Indiana: 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 $\alpha = 0$)
Indiana (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

Indiana

$R_0 = 1.7/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect $= 6/7/9$

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

Indiana

$R_0 = 1.7/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/7/9$

DATA THROUGH 09-OCT-2020

Cumulative deaths per million people
Indiana (7 days): Cumulative Deaths per Million, Log Scale \((\alpha = .05)\)

\[
R_0 = 1.7/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/7/9
\]
Robustness to Mortality Rate, $\delta$
Indiana: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Indiana

$R_0=1.7/1.1/1.1 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 6/7/9$

DATA THROUGH 09-OCT-2020
Indiana: Daily Deaths per Million People ($\delta = 0.01/0.008/0.012$)

Indiana

$R_0 = 1.7/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 6/7/9

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

Indiana

$R_0=1.7/1.1/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 6/7/9

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
Indiana: Re-Opening ($\alpha = 0.05$)

Indiana

$R_0(t)=1.1$, $R_0(\text{suppress})=1.1$, $R_0(25/50)=1.3/1.6$, $\delta = 0.010$, $\alpha=0.05$

(Light bars = New York City, for comparison)
Indiana: Re-Opening ($\alpha = 0$)

Indiana

$R_0(t)=1.2$, $R_0(\text{suppress})=1.1$, $R_0(25/50)=1.4/1.6$, $\delta = 0.010$, $\alpha=0.00$

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

Indiana

$R_0 = 1.7/1.2/1.2$ $\delta = 0.010$ $\alpha = 0.00$ $\theta = 0.1$ $\%$Infect $= 6/7/12$

DATA THROUGH 09-OCT-2020
Indiana (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Indiana

$R_0 = 1.7/1.2/1.2$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 6/7/12

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

Indiana

$R_0 = 1.7/1.2/1.2$ \hspace{1cm} $\delta = 0.010$ \hspace{1cm} $\alpha = 0.00$ \hspace{1cm} $\theta = 0.1$ \hspace{1cm} %Infect = 6/7/12
Indiana: Daily Deaths per Million People \( (\delta = 0.8\%) \)

Indiana

\( R_0 = 1.7/1.1/1.1 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 7/8/11 \)
Indiana: Cumulative Deaths per Million ($\delta = 0.8\%$)

Indiana

$R_0 = 1.7/1.1/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  %Infected = 7/8/11
Indiana: Daily Deaths per Million People ($\delta = 1.2\%$)

Indiana

$R_0 = 1.7/1.1/1.1$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 5/6/8
Indiana: Cumulative Deaths per Million ($\delta = 1.2\%$)

R<sub>0</sub> = 1.7/1.1/1.1  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 5/6/8
Indiana: Daily Deaths per Million People ($\gamma = 0.2/0.15$)

Indiana

$R_0 = 1.7/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 6/7/9$

DATA THROUGH 09-OCT-2020
Indiana: Cumulative Deaths per Million \( \gamma = .2/.15 \)

\[ R_0 = 1.7/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/7/9 \]

DATA THROUGH 09-OCT-2020

Cumulative deaths per million people

Indiana: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Indiana

$R_0=1.7/1.1/1.1 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=6/7/9$

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

Indiana

$R_0 = 1.7/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 6/7/9

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)
Indiana: Daily Deaths, Actual and Smoothed

Indiana: Daily deaths, \( d \)

\( \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \)
Indiana: Change in Smoothed Daily Deaths

Indiana: Delta $d$

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

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