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

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Extended results for Wisconsin
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)
Wisconsin: Daily Deaths per Million People
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)
Wisconsin: Estimates of $R_0(t)$

Wisconsin
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Wisconsin: Percent Currently Infectious

Wisconsin
Peak I/N = 0.13%  Final I/N = 0.05%  δ=0.010  θ=0.10  γ=0.20
Wisconsin: Growth Rate of Daily Deaths over Past Week (percent)

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

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

     \[\Rightarrow \alpha \approx 0.05\]

     *$R_0$ 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 $\alpha = 0$)
Wisconsin (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

Wisconsin

$R_0 = 1.5/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $%\text{Infect} = 2/3/3$

DATA THROUGH 24-AUG-2020
Wisconsin (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

Wisconsin

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 2/3/3$

DATA THROUGH 24-AUG-2020
Wisconsin (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = .05$)

Wisconsin

$R_0=1.5/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%\text{Infect}= 2/3/3$

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan  2020
Robustness to Mortality Rate, $\delta$
Wisconsin: Cumulative Deaths per Million \( (\delta = .01/.008/.012) \)

\[
\text{Wisconsin} \\
R_0=1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 2/3/3
\]

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

Wisconsin

$R_0 = 1.5 / 1.0 / 1.0$  \(\delta = 0.010\)  \(\alpha = 0.05\)  \(\theta = 0.1\)  \%Infect = 2 / 3 / 3

DATA THROUGH 24-AUG-2020
Wisconsin: Cumulative Deaths per Million ($\delta = .01 / .008 / .012$)

Wisconsin

$R_0=1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 2/3/3$

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 $R_0 = \text{“normal”}$
– **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
Wisconsin: Re-Opening \( (\alpha = 0.05) \)

Wisconsin

\[ R_0(t) = 1.0, \quad R_0(\text{suppress}) = 1.0, \quad R_0(25/50) = 1.3/1.5, \quad \delta = 0.010, \quad \alpha = 0.05 \]
Wisconsin: Re-Opening ($\alpha = 0$)

Wisconsin

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

Wisconsin
\[ R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 2/3/3 \]

Data through 24-Aug-2020
Wisconsin (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Wisconsin

$R_0 = 1.5/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$Infect = 2/3/3

DATA THROUGH 24-AUG-2020
Wisconsin (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

$$R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \% \text{Infect} = 2/3/3$$
Wisconsin: Daily Deaths per Million People ($\delta = 0.8\%$)

\[ R_0 = 1.5/1.0/1.0 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 3/3/4 \]
Wisconsin: Cumulative Deaths per Million ($\delta = 0.8\%$)

Wisconsin

$R_0 = 1.5/1.0/1.0 \delta = 0.008 \ \theta = 0.1 \ \gamma = 0.2 \ \%\text{Infect} = 3/3/4$
Wisconsin: Daily Deaths per Million People ($\delta = 1.2\%$)

Wisconsin

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 2/2/3$
Wisconsin: Cumulative Deaths per Million ($\delta = 1.2\%$)

Wisconsin

$R_0 = 1.5/1.0/1.0$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect = 2/2/3
Wisconsin: Daily Deaths per Million People ($\gamma = .2 / .15$)

Wisconsin

$R_0 = 1.5/1.0/1.0$ \hspace{0.5cm} $\delta = 0.010$ \hspace{0.5cm} $\alpha = 0.05$ \hspace{0.5cm} $\theta = 0.1$ \hspace{0.5cm} $\%$ Infect = 2/3/3

DATA THROUGH 24-AUG-2020
Wisconsin: Cumulative Deaths per Million $\gamma = .2/.15$)

Wisconsin

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%Infected = 2/3/3$

$\gamma = 0.25$

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

Wisconsin

$R_0=1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=2/3/3$

Data through 24-Aug-2020

Daily deaths per million people

Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, 2020
Wisconsin: Cumulative Deaths per Million People ($\theta = .1 / .07 / .2$)

Wisconsin

$R_0 = 1.5/1.0/1.0 \ \delta = 0.010 \ \alpha = 0.05 \ \theta = 0.1 \ %\text{Infect} = 2/3/3$

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)
Wisconsin: Daily Deaths, Actual and Smoothed

Wisconsin: Daily deaths, $d$

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

Wisconsin: Delta (Δ d)

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