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

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Extended results for Minnesota
Based on data through September 11, 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)
Minnesota: Daily Deaths per Million People

![Graph showing daily deaths per million people in Minnesota from April to September 2020. The y-axis represents daily deaths per million people, and the x-axis represents the months from April to September 2020. The graph displays fluctuations in daily deaths throughout the period.]
Minnesota: 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)
Minnesota: Estimates of $R_0(t)$

Minnesota

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

Minnesota

Peak I/N = 0.25%  Final I/N = 0.05%  δ = 0.010  θ = 0.10  γ = 0.20
Minnesota: 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 $\alpha = 0$)
Minnesota (7 days): Daily Deaths per Million People ($\alpha = .05$)

Minnesota

$R_0 = 1.5/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%Infect = 4/4/6$

DATA THROUGH 11-SEP-2020
Minnesota (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

Minnesota

$R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 4/4/6$

DATA THROUGH 11-SEP-2020
Minnesota (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = .05$)

Minnesota
$R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 4/4/6$

New York City
Italy
Robustness to Mortality Rate, $\delta$
Minnesota: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

Minnesota

$R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}= 4/4/6$

DATA THROUGH 11-SEP-2020
Minnesota: Daily Deaths per Million People ($\delta = .01/.008/.012$)

Minneapolis

$R_0 = 1.5/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect = 4/4/6

DATA THROUGH 11-SEP-2020
Minnesota: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

Minnesota

$R_0 = 1.5/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 4/4/6

DATA THROUGH 11-SEP-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 $R_0 = “normal”$
– Purple: we move 50% of the way from $R_0(today)$ back to initial $R_0 = “normal”$

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

Minnesota

$R_0(t)=1.1, \ R_0\text{ (suppress)}=1.0, \ R_0\text{ (25/50)}=1.3/1.5, \ \delta = 0.010, \ \alpha=0.05$

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

Minnesota

$R_0(t) = 1.1$, $R_0(\text{suppress}) = 1.0$, $R_0(25/50) = 1.3/1.5$, $\delta = 0.010$, $\alpha = 0.00$

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

Minnesota

$R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 4/4/6$

DATA THROUGH 11-SEP-2020
Minnesota (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)


Cumulative deaths per million people

Minnesota

$R_0 = 1.5/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$Infect $= 4/4/6$

DATA THROUGH 11-SEP-2020
Minnesota (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

Minnesota

$R_0=1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha=0.00 \quad \theta=0.1 \quad \%\text{Infect}=4/4/6$

New York City

Italy

Cumulative deaths per million people

Minnesota: Daily Deaths per Million People ($\delta = 0.8\%$)

Minnesota
$R_0 = 1.5/1.1/1.1$  \( \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%Infect = 5/5/7 \)
Minnesota: Cumulative Deaths per Million ($\delta = 0.8\%$)

**Minnesota**

$R_0=1.5/1.1/1.1$  $\delta = 0.008$  $\theta=0.1$  $\gamma=0.2$  $\%Infect= 5/ 5/ 7$
Minnesota: Daily Deaths per Million People ($\delta = 1.2\%$)

Minnesota

$R_0=1.5/1.1/1.0$  \( \delta = 0.012 \)  \( \theta = 0.1 \)  \( \gamma = 0.2 \)  \%Infect= 3/4/5
Minnesota: Cumulative Deaths per Million ($\delta = 1.2\%$)

Minnesota

$R_0 = 1.5/1.1/1.0 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 3/4/5$
Minnesota: Daily Deaths per Million People ($\gamma = .2/.15$)

Minnesota

$R_0 = 1.5/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 4/4/6

DATA THROUGH 11-SEP-2020
Minnesota: Cumulative Deaths per Million $\gamma = .2/.15$)

Minnesota

$R_0=1.5/1.1/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 4/ 4/ 6

$\gamma = 0.25$
Minnesota: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Minnesota

$R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 4/4/6$

DATA THROUGH 11-SEP-2020
Minnesota: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

Minnesota

$R_0 = 1.5/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect$= 4/4/6$

DATA THROUGH 11-SEP-2020
Data Underlying Estimates of Time-Varying $R_0$

– Inferred from daily deaths, and
– the change in daily deaths, and
– the change in \( \text{(the change in daily deaths)} \)
Minnesota: Daily Deaths, Actual and Smoothed

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

![Chart showing Minnesota: Delta d with values δ = 0.010, θ = 0.10, γ = 0.20]
Minnesota: Change in (Change in Smoothed Daily Deaths)

Minnesota: Delta (Delta d)

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