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

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Extended results for Nebraska
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:
  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)
Nebraska: 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)
Nebraska: Estimates of $R_0(t)$

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

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

Nebraska
\( \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \)
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:
  - Alternatively, we fit this equation:
    \[
    \log R_0(t) = a_0 - \alpha(Daily\ Deaths)
    \]
    \[
    \Rightarrow \alpha \approx .05
    \]
    \[R_0 \text{ declines by 5 percent for each new daily death,}
    \]
    \[or\ rises\ by\ 5\ percent\ when\ daily\ deaths\ decline\]

- 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 $\alpha = 0$)
Nebraska (7 days): Daily Deaths per Million People (\(\alpha = 0.05\))

Nebraska

\(R_0 = 1.3/1.0/1.0\)  \(\delta = 0.010\)  \(\alpha = 0.05\)  \(\theta = 0.1\)  \%Infect = 4/4/6

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

$R_0 = 1.3/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect = 4/4/6

DATA THROUGH 09-OCT-2020
Nebraska (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0.05$)

Nebraska

$R_0 = 1.3/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 4/4/6
Robustness to Mortality Rate, $\delta$
Nebraska: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Nebraska

$R_0=1.3/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 4/4/6

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

Nebraska

$R_0 = 1.3/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 4/4/6

DATA THROUGH 09-OCT-2020
Nebraska: Cumulative Deaths per Million (δ = .01/.008/.012)

\[ R_0 = 1.3/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 4/4/6 \]

DATA THROUGH 09-OCT-2020
Reopening and Herd Immunity

– Black: assumes $R_0(today)$ remains in place forever
– Red: assumes $R_0(\text{suppress}) = 1/s(today)$
– 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
Nebraska: Re-Opening ($\alpha = .05$)

Nebraska

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

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

Nebraska

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

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

Nebraska

$R_0 = 1.3/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 4/4/6

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

Nebraska

$R_0 = 1.3/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%\text{Infect} = 4/4/6$

DATA THROUGH 09-OCT-2020

Cumulative deaths per million people
Nebraska (7 days): Cumulative Deaths per Million, Log Scale \( (\alpha = 0) \)

\[ R_0 = 1.3/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 4/4/6 \]
Nebraska: Daily Deaths per Million People ($\delta = 0.8\%$)

Nebraska

$R_0 = 1.3/1.0/1.1 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \text{%Infect} = 4/5/7$
Nebraska: Cumulative Deaths per Million ($\delta = 0.8\%$)

Nebraska

$R_0 = 1.3/1.0/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 4/5/7
Nebraska: Cumulative Deaths per Million ($\delta = 1.2\%$)

Nebraska

$R_0 = 1.3/1.0/1.0$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $%Infect = 3/4/5$
Nebraska: Daily Deaths per Million People ($\gamma = .2/.15$)

Nebraska

$R_0=1.3/1.0/1.0 \quad \delta = 0.010 \quad \theta=0.1 \quad \gamma=0.2 \quad \%\text{Infect}= 4/4/6$
Nebraska: Cumulative Deaths per Million $\gamma = .2 / .15$}

Nebraska

$R_0 = 1.3 / 1.0 / 1.0 \quad \delta = 0.010 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \% \text{Infect} = 4 / 4 / 6$
Nebraska: Daily Deaths per Million People ($\theta = .1 /.07 / .2$)

Nebraska

$R_0 = 1.2/1.0/1.1$  $\delta = 0.010$  $\theta = 0.2$  $\gamma = 0.2$  $\%$Infect = 4/4/6
Nebraska: Cumulative Deaths per Million People ($\theta = .1 / .07 / .2$)

Nebraska

$R_0 = 1.2 / 1.0 / 1.1$  $\delta = 0.010$  $\theta = 0.2$  $\gamma = 0.2$  $\%$ Infect $= 4 / 4 / 6$
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)
Nebraska: Daily Deaths, Actual and Smoothed

Nebraska: Daily deaths, $d$

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

Nebraska: Delta $d$

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

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