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

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Extended results for Connecticut
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)
Connecticut: Daily Deaths per Million People

Connecticut
**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)
Connecticut: Estimates of $R_0(t)$

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

Connecticut
Peak I/N = 1.61%  Final I/N = 0.03%  δ = 0.010  θ=0.10  γ=0.20
Connecticut: 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:

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

  $$\Rightarrow \alpha \approx .05$$

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

Connecticut

$R_0=2.2/1.4/1.2 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=13/13/16$

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

Connecticut

$R_0=2.2/1.4/1.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}=13/13/16$

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

**Connecticut**

$R_0 = 2.2/1.4/1.2$  \( \delta = 0.010 \)  \( \alpha = 0.05 \)  \( \theta = 0.1 \)  \%Infect = 13/13/16
Robustness to Mortality Rate, \( \delta \)
Connecticut: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

Connecticut

$R_0 = 2.2/1.4/1.2$  \( \delta = 0.010 \)  \( \alpha=0.05 \)  \( \theta=0.1 \)  \%Infect=13/13/16

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

Connecticut

$R_0 = 2.2/1.4/1.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 13/13/16$

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

Connecticut

$R_0 = 2.2/1.4/1.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 13/13/16$

DATA THROUGH 09-OCT-2020

Cumulative deaths per million people

0 200 400 600 800 1000 1200 1400 1600

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
Connecticut: Re-Opening ($\alpha = .05$)

Connecticut

$R_0(t)=1.4, \ R_0(\text{suppress})=1.2, \ R_0(25/50)=1.6/1.8, \ \delta = 0.010, \ \alpha=0.05$

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

Connecticut

$R_0(t)=1.4$, $R_0(\text{suppress})=1.2$, $R_0(25/50)=1.6/1.8$, $\delta = 0.010$, $\alpha=0.00$

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

R$_0$=2.2/1.4/1.4  $\delta$ = 0.010  $\alpha$=0.00  $\theta$=0.1  %Infect=13/13/24

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

Connecticut

$R_0 = 2.2/1.4/1.4 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect}=13/13/24$

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

Connecticut

$R_0 = 2.2/1.4/1.4 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 13/13/24$
Connecticut: Daily Deaths per Million People ($\delta = 0.8\%$)

Connecticut

$R_0 = 2.2/1.4/1.2$  $\delta = 0.008$  $\theta=0.1$  $\gamma=0.2$  %Infect=16/17/20
Connecticut: Cumulative Deaths per Million ($\delta = 0.8\%$)
Connecticut: Daily Deaths per Million People ($\delta = 1.2\%$)

Connecticut

$R_0 = 2.2/1.3/1.1$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%Infect = 11/11/13$
Connecticut: Cumulative Deaths per Million ($\delta = 1.2\%$)

Connecticut

$R_0 = 2.2/1.3/1.1 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 11/11/13$
Connecticut: Daily Deaths per Million People ($\gamma = .2 / .15$)

R$_0$ = 2.2/1.4/1.2  \(\delta = 0.010\)  \(\alpha = 0.05\)  \(\theta = 0.1\)  \%Infect = 13/13/16

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

Connecticut

$R_0 = 2.2/1.4/1.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 13/13/16$

DATA THROUGH 09-OCT-2020

Cumulative deaths per million people

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

Connecticut

$R_0=2.2/1.4/1.2$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect=13/13/16

DATA THROUGH 09-OCT-2020
Connecticut: Cumulative Deaths per Million People (θ = .1/.07/.2)

Connecticut

$R_0 = 2.2/1.4/1.2 \; \delta = 0.010 \; \alpha = 0.05 \; \theta = 0.1 \; \%\text{Infect}=13/13/16$

DATA THROUGH 09-OCT-2020

θ = 0.1
θ = 0.2
θ = 0.07
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)
Connecticut: Daily Deaths, Actual and Smoothed

Connecticut: Daily deaths, d
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Connecticut: Change in Smoothed Daily Deaths

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

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