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

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

Delaware

Daily deaths per million people

Delaware

Apr May Jun Jul Aug Sep

-10

0

10

20

30

40

50

60

70

80

Apr May Jun Jul Aug Sep

2020
Delaware: 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)
Delaware: Estimates of $R_0(t)$

Delaware

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

Delaware
Peak I/N = 0.45%  Final I/N = 0.27%  δ = 0.010  θ=0.10  γ=0.20
Delaware: 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 $R_0(t) = \text{final empirical value}$. 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 $\alpha = 0$)
Delaware (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

Delaware

$R_0=1.5/0.3/0.3 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=6/6/6$

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

Delaware

$R_0 = 1.5/0.3/0.3 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6$

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

Delaware

$R_0 = 1.5/0.3/0.3 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6$

New York City

Italy
Robustness to Mortality Rate, $\delta$
Delaware: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Delaware

$R_0 = 1.5/0.3/0.3$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 6/6/6$

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

Delaware

$R_0 = 1.5 / 0.3 / 0.3 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6 / 6 / 6$

DATA THROUGH 11-SEP-2020

Daily deaths per million people

Apr May Jun Jul Aug Sep Oct Nov Dec Jan 2020
Delaware: Cumulative Deaths per Million \((\delta = .01/.008/.012)\)

Data through 11-Sep-2020

\[ R_0 = 1.5/0.3/0.3 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6 \]

\[ \delta = 0.008 \]
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 $R_0 = \text{“normal”}$
– 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
Delaware: Re-Opening (χ = .05)

Delaware

$R_0(t) = 0.3, \ R_0(\text{suppress}) = 1.1, \ R_0(25/50) = 0.7/1.1, \ \delta = 0.010, \ \alpha = 0.05$

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

Delaware

$R_0(t)=0.2$, $R_0(\text{suppress})=1.1$, $R_0(25/50)=0.7/1.1$, $\delta = 0.010$, $\alpha=0.00$

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

Delaware

$R_0 = 1.5/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.00 \quad \theta=0.1 \quad \%Infect= 6/6/6$

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

Delaware

$R_0=1.5/0.2/0.2$  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  $%\text{Infect}= 6/6/6$

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

Delaware

$R_0=1.5/0.2/0.2$  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  $\%$Infect= 6/6/6

New York City

Italy

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan  2020
Delaware: Daily Deaths per Million People ($\delta = 0.8\%$)

Delaware

$R_0 = 1.5/0.3/0.3$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%Infect = 7/7/7$

SOME ERRORS IN ESTIMATION...
Delaware: Cumulative Deaths per Million (\( \delta = 0.8\% \))

\[
R_0 = 1.5/0.3/0.3 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 7/7/7
\]

SOME ERRORS IN ESTIMATION...
Delaware: Daily Deaths per Million People (δ = 1.2%)
Delaware: Cumulative Deaths per Million ($\delta = 1.2\%$)

$R_0 = 1.5/0.3/0.3 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 5/5/5$

SOME ERRORS IN ESTIMATION...
Delaware: Daily Deaths per Million People ($\gamma = .2/.15$)

Delaware

$R_0=1.5/0.3/0.3 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6$

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

Delaware

$R_0=1.5/0.3/0.3 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 6/6/6$

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

![Graph showing daily deaths per million people in Delaware from April to January 2020. The $R_0$ is 1.5/0.3/0.3, $\delta = 0.010$, $\alpha = 0.05$, $\theta = 0.1$, and %Infect = 6/6/6. Data through 11-Sep-2020.]
Delaware: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

\[ R_0 = 1.5/0.3/0.3 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/6/6 \]

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 (the change in daily deaths)
Delaware: Daily Deaths, Actual and Smoothed

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

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

Delaware: Delta (Delta $d$)

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$