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

Jesús Fernández-Villaverde and Chad Jones

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

Washington

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

Washington
Peak I/N = 0.17%    Final I/N = 0.04%    δ=0.010    θ=0.10    γ=0.20
Washington: Growth Rate of Daily Deaths over Past Week (percent)

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

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

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

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

Washington

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%Infect = 3/\ 3/\ 4$

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

$R_0=1.5/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 3/ 3/ 4

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

Washington

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 3/3/4$
Robustness to Mortality Rate, $\delta$
Washington: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Washington

$R_0=1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=3/3/4$

DATA THROUGH 09-OCT-2020
Washington: Daily Deaths per Million People ($\delta = .01/.008/.012$)

Washington

$R_0=1.5/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%\text{Infect}=3/3/4$

DATA THROUGH 09-OCT-2020

Washington: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

Washington

$R_0 = 1.5/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 3/3/4

DATA THROUGH 09-OCT-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
Washington: Re-Opening ($\alpha = .05$)

Washington

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

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

Washington

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

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

Washington

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 3/3/4$

DATA THROUGH 09-OCT-2020

Daily deaths per million people

Washington (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Washington

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect}=3/3/4$

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

Washington
$R_0 = 1.5/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $%\text{Infect} = 3/3/4$

New York City

Italy

Cumulative deaths per million people
Washington: Daily Deaths per Million People ($\delta = 0.8\%$)

\begin{align*}
\text{Washington} \\
R_0 &= 1.5/1.0/1.0 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 4/4/5
\end{align*}
Washington: Cumulative Deaths per Million ($\delta = 0.8\%$)

Washington

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 4/4/5$
Washington: Daily Deaths per Million People \((\delta = 1.2\%)\)

\begin{align*}
\text{Washington} \\
R_0 &= 1.5/1.0/1.0 \\
\delta &= 0.012 \\
\theta &= 0.1 \\
\gamma &= 0.2 \\
\%\text{Infect} &= 2/3/3
\end{align*}
Washington: Cumulative Deaths per Million ($\delta = 1.2\%$)

Washington

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

- $R_0 = \frac{1.5}{1.0/1.0}$
- $\delta = 0.010$
- $\alpha = 0.05$
- $\theta = 0.1$
- %Infect = 3/3/4

DATA THROUGH 09-OCT-2020
Washington: Cumulative Deaths per Million \( \gamma = .2/.15 \)
Washington: Daily Deaths per Million People ($\theta = .1/.07/.2$)

$R_0 = 1.5/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 3/3/4$

DATA THROUGH 09-OCT-2020
Washington: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

Washington

$R_0 = 1.5/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 3/3/4

DATA THROUGH 09-OCT-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)
Washington: Daily Deaths, Actual and Smoothed

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

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Washington: Delta (Δd)

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