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

Jesús Fernández-Villaverde and Chad Jones

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

California

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

California

Peak I/N = 0.18%  Final I/N = 0.08%  δ=0.010  θ=0.10  γ=0.20
California: Growth Rate of Daily Deaths over Past Week (percent)

California

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

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

$$\Rightarrow \alpha \approx 0.05$$

$R_0$ declines by 5 percent for each new daily death, or rises by 5 percent when daily deaths decline

- Robustness: Assume $R_0(t) =$ 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 $\alpha = 0$)
California (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

California

$R_0 = 1.4/0.9/0.9$  \( \delta = 0.010 \)  \( \alpha = 0.05 \)  \( \theta = 0.1 \)  \%Infect = 4/5/5

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

California

$R_0=1.4/0.9/0.9$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%\text{Infect}=4/5/5$

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

California

$R_0 = 1.4/0.9/0.9$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 4/5/5

Cumulative deaths per million people

New York City

Italy

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

California

$R_0 = 1.4 / 0.9 / 0.9$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 4/ 5/ 5

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

DATA THROUGH 09-OCT-2020

California

$R_0$=1.4/0.9/0.9  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 4/ 5/ 5
California: Cumulative Deaths per Million ($\delta = .01 / .008 / .012$)

California

$R_0 = 1.4 / 0.9 / 0.9$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 4/5/5

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

California

$R_0(t)=0.9$, $R_0(\text{suppress})=1.0$, $R_0(25/50)=1.2/1.4$, $\delta = 0.010$, $\alpha=0.05$

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

California

$R_0(t)=0.9$, $R_0\text{ (suppress)}=1.0$, $R_0(25/50)=1.1/1.4$, $\delta = 0.010$, $\alpha=0.00$

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

California

$R_0 = 1.4/0.9/0.9 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 4/5/5$

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

California

$R_0 = 1.4/0.9/0.9 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 4/5/5$

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

California

$R_0 = 1.4/0.9/0.9$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $%_{\text{Infect}} = 4/5/5$

(Raw data: [California](https://www.cdc.gov/coronavirus/2019-ncov/cases-in-us.html))
California: Daily Deaths per Million People ($\delta = 0.8\%$)
California: Cumulative Deaths per Million ($\delta = 0.8\%$)

California

$R_0 = 1.4/0.9/1.0 \delta = 0.008 \theta = 0.1 \gamma = 0.2 \%Infect = 5/6/6$
California: Daily Deaths per Million People ($\delta = 1.2\%$)

California

$R_0 = 1.4/0.9/0.9 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 4/4/4$
California: Cumulative Deaths per Million ($\delta = 1.2\%$)

California

$R_0 = 1.4/0.9/0.9$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect$= 4/4/4$
California: Daily Deaths per Million People ($\gamma = .2/.15$)

California

$R_0=1.4/0.9/0.9$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 4/ 5/ 5

DATA THROUGH 09-OCT-2020
California: Cumulative Deaths per Million $\gamma = 0.15$}

$R_0 = 1.4/0.9/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 4/5/5$

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

California

$R_0 = 1.4 / 0.9 / 0.9$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 4 / 5 / 5

DATA THROUGH 09-OCT-2020
California: Cumulative Deaths per Million People ($\theta = 0.1 / 0.07 / 0.2$)

California

$R_0 = 1.4 / 0.9 / 0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}= 4 / 5 / 5$

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)
California: Daily Deaths, Actual and Smoothed

California: Daily deaths, $d$

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

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

[Graph showing changes in smoothed daily deaths for California from February to October 2020]