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

Jesús Fernández-Villaverde and Chad Jones

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

[Chart showing daily deaths per million people in Sweden from April to October 2020]
Sweden: 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 $t$ ($\frac{\beta_t}{\gamma}$)</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)
Sweden: Estimates of $R_0(t)$

Sweden

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

![Graph showing Sweden's percent currently infectious from March to October 2020. The peak I/N is 0.54% in April, and the final I/N is 0.01%. The rates are 0.010, 0.10, 0.20.](image-url)
Sweden: Growth Rate of Daily Deaths over Past Week (percent)

Growth rate of daily deaths (percent, past week)

Sweden

\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
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 $\alpha = 0$)
Sweden (7 days): Daily Deaths per Million People (\( \alpha = .05 \))

Sweden

\[ R_0 = 1.9/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6 \]

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

DATA THROUGH 09-OCT-2020

Sweden
$R_0=1.9/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 6/6/6$
Sweden (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = .05$)

$$R_0 = 1.9/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%Infect = 6/6/6$$

- **Sweden**
- **New York City**
- **Italy**

Cumulative deaths per million people

Robustness to Mortality Rate, $\delta$
Sweden: Cumulative Deaths per Million ($\delta = .01/0.008/0.012$)

Swedish data through 09-OCT-2020
Sweden: Daily Deaths per Million People ($\delta = .01/.008/.012$)

Sweden

$R_0 = 1.9/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect = 6/6/6

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

Sweden

$R_0 = 1.9/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  \%Infect $= 6/6/6$

$\delta = 0.008$

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

Sweden

$R_0(t)=0.2, \ R_0\ (\text{suppress})=1.1, \ R_0(25/50)=0.7/1.1, \ \delta = 0.010, \ \alpha=0.05$

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

Sweden

$R_0(t)=0.2$, $R_0$ (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
Sweden (7 days): Daily Deaths per Million People ($\alpha = 0$)

$R_0=1.9/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.00 \quad \theta=0.1 \quad \%\text{Infected}=6/6/6$

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

Sweden

$R_0 = 1.9/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%Infect = 6/6/6$

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

Sweden

$R_0 = 1.9/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$ Infect = 6/6/6
Sweden: Daily Deaths per Million People ($\delta = 0.8\%$)

Swedish data shows:

- $R_0 = 1.9/0.2/0.2$
- $\delta = 0.008$
- $\theta = 0.1$
- $\gamma = 0.2$
- $\%\text{Infect} = 7/7/7$

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

Sweden

$R_0=1.9/0.2/0.2 \quad \delta = 0.008 \quad \theta=0.1 \quad \gamma=0.2 \quad %\text{Infect}= 7/7/7$

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

Sweden

$R_0=1.9/0.2/0.2 \quad \delta = 0.012 \quad \theta=0.1 \quad \gamma=0.2 \quad \%\text{Infect}=5/5/5$

SOME ERRORS IN ESTIMATION...
Sweden: Cumulative Deaths per Million ($\delta = 1.2\%$)

Sweden

$R_0=1.9/0.2/0.2 \quad \delta = 0.012 \quad \theta=0.1 \quad \gamma=0.2 \quad \%\text{Infect}= 5/5/5$

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

**Sweden**

\(R_0 = 1.9/0.2/0.2\) \(\delta = 0.010\) \(\alpha = 0.05\) \(\theta = 0.1\) \%Infect = 6/6/6

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

Sweden

$R_0=1.9/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=6/6/6$

$\gamma = 0.2 \quad \frac{1}{\gamma} = 0.15$

DATA THROUGH 09-OCT-2020
Sweden: Daily Deaths per Million People ($\theta = 1/0.07/0.2$)

- $R_0=1.9/0.2/0.2$  
- $\delta = 0.010$  
- $\alpha = 0.05$  
- $\theta = 0.1$  
- %Infect = 6/6/6

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

DATA THROUGH 09-OCT-2020

Sweden

$R_0=1.9/0.2/0.2$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  \%Infect= 6/ 6/ 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)
Sweden: Daily Deaths, Actual and Smoothed

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

Swedish Delta $d$

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

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