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

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Extended results for Stockholm, Sweden
Based on data through August 24, 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)
Stockholm, Sweden: Daily Deaths per Million People
Stockholm, 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 $t$ ($\beta_t/\gamma$)</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)
Stockholm, Sweden: Estimates of $R_0(t)$

Stockholm, Sweden
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Stockholm, Sweden: Percent Currently Infectious

Stockholm, Sweden
Peak I/N = 1.68%   Final I/N = 0.03%   δ = 0.010   θ = 0.10   γ = 0.20
Stockholm, Sweden: Growth Rate of Daily Deaths over Past Week (percent)
Notes on Intepreting 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 $\alpha = 0$)
Stockholm, Sweden (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

Stockholm, Sweden

$R_0=2.2/0.2/0.2$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect=15/15/15

DATA THROUGH 24-AUG-2020
Stockholm, Sweden (7 days): Cumulative Deaths per Million (Future, α)

Stockholm, Sweden
\[ R_0 = 2.2/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 15/15/15 \]

DATA THROUGH 24-AUG-2020
Stockholm, Sweden (7 days): Cumulative Deaths per Million, Log Scale

Stockholm, Sweden

$R_0 = 2.2 / 0.2 / 0.2$  \( \delta = 0.010 \)  \( \alpha = 0.05 \)  \( \theta = 0.1 \)  \%Infect = 15/15/15
Robustness to Mortality Rate, $\delta$
Stockholm, Sweden: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 15/15/15$

DATA THROUGH 24-AUG-2020
Stockholm, Sweden: Daily Deaths per Million People ($\delta = .01/0.008/0.012$)

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}=15/15/15$

DATA THROUGH 24-AUG-2020
Stockholm, Sweden: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}=15/15/15$

$\delta = 0.008$

DATA THROUGH 24-AUG-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
Stockholm, Sweden: Re-Opening ($\alpha = .05$)

Stockholm, Sweden

$R_0(t)=0.2, \ R_0\ (\text{suppress})=1.2, \ R_0\ (25/50)=0.7/1.2, \ \delta = 0.010, \ \alpha=0.05$
Stockholm, Sweden: Re-Opening ($\alpha = 0$)

Stockholm, Sweden

$R_0(t)=0.2$, $R_0(suppress)=1.2$, $R_0(25/50)=0.7/1.2$, $\delta = 0.010$, $\alpha=0.00$
Results for alternative parameter values
Stockholm, Sweden (7 days): Daily Deaths per Million People ($\alpha = 0$)

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%\text{Infect} = 15/15/15$

DATA THROUGH 24-AUG-2020
Stockholm, Sweden (7 days): Cumulative Deaths per Million (Future, $\alpha$)

Stockholm, Sweden

$R_0=2.2/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.00 \quad \theta=0.1 \quad \%\text{Infect}=15/15/15$

DATA THROUGH 24-AUG-2020
Stockholm, Sweden (7 days): Cumulative Deaths per Million, Log Scale

Stockholm, Sweden

\[ R_0 = 2.2/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 15/15/15 \]
Stockholm, Sweden: Daily Deaths per Million People ($\delta = 0.8\%$)

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 18/18/18$

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

Stockholm, Sweden

$R_0=2.2/0.2/0.2$  $\delta = 0.008$  $\theta=0.1$  $\gamma=0.2$  $\%Infect=18/18/18$

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

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect = 12/12/12

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

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%\text{Infect} = 12/12/12$

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

Stockholm, Sweden

$R_0 = 2.2 / 0.2 / 0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 15 / 15 / 15$

DATA THROUGH 24-AUG-2020
Stockholm, Sweden: Cumulative Deaths per Million $\gamma = .2/.15$.

Cumulative deaths per million people

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect}=15/15/15$

DATA THROUGH 24-AUG-2020
Stockholm, Sweden: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Stockholm, Sweden
$R_0=2.2/0.2/0.2$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect=15/15/15

DATA THROUGH 24-AUG-2020
Stockholm, Sweden: Cumulative Deaths per Million People ($\theta = 0.1 / 0.07$)

Stockholm, Sweden

$R_0 = 2.2/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect = 15/15/15

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  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)
Stockholm, Sweden: Daily Deaths, Actual and Smoothed

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

Stockholm, Sweden: Delta $d$

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

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