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

Jesús Fernández-Villaverde and Chad Jones

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

Daily deaths per million people

Netherlands

Apr | May | Jun | Jul | Aug | Sep 2020

-2 0 2 4 6 8 10 12 14
Netherlands: Daily Deaths per Million People (Smoothed)

Daily deaths per million people (smoothed)

Netherlands
## Brief Summary of Model

- See the paper for a full exposition
- A 5-state SIRDC model with a time-varying $R_0$

### Parameter Baseline Description

<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)
Netherlands: Estimates of $R_0(t)$

Netherlands
\[ \delta = 0.010 \quad \theta=0.10 \quad \gamma=0.20 \]
Netherlands: Percent Currently Infectious

Peak I/N = 0.50%  Final I/N = 0.00%  \( \delta = 0.010 \)  \( \theta = 0.10 \)  \( \gamma = 0.20 \)
Netherlands: 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:

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

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

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

Netherlands

$R_0 = 1.8/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 4/4/4

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

\[ R_0 = 1.8/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 4/4/4 \]

DATA THROUGH 11-SEP-2020
Netherlands (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0.05$)

R$_0$=1.8/0.2/0.2  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 4/ 4/ 4
Robustness to Mortality Rate, $\delta$
Netherlands: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Netherlands

$R_0=1.8/0.2/0.2$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%\text{Infect}=4/4/4$

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

United States

$R_0=1.8/0.2/0.2 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 4/4/4$

DATA THROUGH 11-SEP-2020
Netherlands: Cumulative Deaths per Million ($\delta = 0.01/0.008/0.012$)

Netherlands

$R_0 = 1.8/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 4/4/4$

DATA THROUGH 11-SEP-2020

$\delta = 0.008$
Reopening and Herd Immunity

- **Black**: assumes $R_0(\text{today})$ remains in place forever
- **Red**: assumes $R_0(\text{supress}) = 1/s(\text{today})$
- **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
Netherlands: Re-Opening ($\alpha = .05$)

Netherlands

$R_0(t) = 0.2$, $R_0(\text{suppress}) = 1.0$, $R_0(25/50) = 0.7/1.1$, $\delta = 0.010$, $\alpha = 0.05$

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

Netherlands

$R_0(t)=0.2$, $R_0\text{(suppress)}=1.0$, $R_0(25/50)=0.7/1.1$, $\delta = 0.010$, $\alpha=0.00$

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

\[ R_0 = 1.8/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 4/4/4 \]
Netherlands (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Netherlands

$R_0 = 1.8/0.2/0.2$, $\delta = 0.010$, $\alpha = 0.00$, $\theta = 0.1$, %Infect $= 4/4/4$

DATA THROUGH 11-SEP-2020
Netherlands: Daily Deaths per Million People ($\delta = 0.8\%$)

Netherlands

$R_0 = 1.8/0.2/0.2$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect = 4/4/4

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

Netherlands

$R_0 = 1.8/0.2/0.2$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$ Infect = 4/4/4

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

Netherlands
\[ R_0 = 1.8/0.2/0.2 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 3/3/3 \]

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

R_0 = 1.8/0.2/0.2  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  %Infec= 3/3/3

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

Netherlands

$R_0 = 1.8/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 4/4/4$

DATA THROUGH 11-SEP-2020
Netherlands: Cumulative Deaths per Million $\gamma = 0.2/0.15$)

DATA THROUGH 11-SEP-2020

Netherlands

$R_0 = 1.8/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 4/4/4

$\gamma = 0.25$
Netherlands: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Netherlands

$R_0 = 1.8/0.2/0.2 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 4/4/4$

DATA THROUGH 11-SEP-2020

Netherlands: Daily Deaths per Million People ($\theta = .1/.07/.2$)
Netherlands: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

Netherlands

$R_0 = 1.8/0.2/0.2$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect= 4/ 4/ 4

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)
Netherlands: Daily Deaths, Actual and Smoothed

Netherlands: Daily deaths, \( d \)

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

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

Netherlands: Delta (Delta d)

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