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

Jesús Fernández-Villaverde and Chad Jones

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

$\delta = 0.010 \quad \theta = 0.1 \quad \gamma = 0.20$
Italy: Percent Currently Infectious

Peaks I/N = 0.74%  Final I/N = 0.01%  δ = 0.010  Θ = 0.10  γ = 0.20
Italy: 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:

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

\[\Rightarrow \alpha \approx 0.05\]

$R_0$ 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 $\alpha = 0$)
Italy (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

$R_0 = 2.0/1.3/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/8$

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

$R_0 = 2.0/1.3/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \%$Infect$= 6/6/8$

DATA THROUGH 11-SEP-2020
Italy (7 days): Cumulative Deaths per Million, Log Scale (α = .05)

Italy

$R_0 = 2.0/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 6/6/8
Robustness to Mortality Rate, $\delta$
Italy: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

$R_0 = 2.0/1.3/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/6/8$

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

R$_0$ = 2.0/1.3/1.1  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 6/6/8

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

DATA THROUGH 11-SEP-2020

Italy

$R_0 = 2.0/1.3/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 6/6/8

$\delta = 0.008$
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
Italy: Re-Opening ($\alpha = .05$)

Italy

$R_0(t)=1.3$, $R_0(\text{suppress})=1.1$, $R_0(25/50)=1.5/1.7$, $\delta = 0.010$, $\alpha=0.05$

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

Italy

$R_0(t)=1.3, \ R_0(\text{suppress})=1.1, \ R_0(25/50)=1.5/1.7, \ \delta = 0.010, \ \alpha=0.00$

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

$R_0 = 2.0/1.3/1.3$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 6/6/10

DATA THROUGH 11-SEP-2020
Italy (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

$R_0 = 2.0/1.3/1.3$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 6/6/10

DATA THROUGH 11-SEP-2020
Italy (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

Country: Italy

- $R_0 = 2.0 / 1.3 / 1.3$
- $\delta = 0.010$
- $\alpha = 0.00$
- $\theta = 0.1$
- %Infected: 6/6/10
Italy: Daily Deaths per Million People ($\delta = 0.8\%$)

$R_0 = 2.0/1.3/1.1 \; \delta = 0.008 \; \theta = 0.1 \; \gamma = 0.2 \; \%Infect = 7/8/10$
Italy: Cumulative Deaths per Million ($\delta = 0.8\%$)

Italy

$R_0 = 2.0/1.3/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect$= 7/8/10$
Italy: Daily Deaths per Million People ($\delta = 1.2\%$)

$R_0 = 2.0/1.3/1.1$, $\delta = 0.012$, $\theta = 0.1$, $\gamma = 0.2$, $\%$Infect $= 5/5/7$
Italy: Cumulative Deaths per Million ($\delta = 1.2\%$)

Italy

$R_0 = 2.0/1.3/1.1$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $%\text{Infect} = 5/5/7$
Italy: Daily Deaths per Million People ($\gamma = .2/.15$)

$R_0=2.0/1.3/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 6/6/8

DATA THROUGH 11-SEP-2020
Italy: Cumulative Deaths per Million $\gamma = .2/.15$)

$I_t=2.0/1.3/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $%\text{Infect} = 6/6/8$

DATA THROUGH 11-SEP-2020
Italy: Daily Deaths per Million People ($\theta = .1/.07/.2$)

\[ R_0 = 2.0/1.3/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/8 \]

DATA THROUGH 11-SEP-2020
Italy: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

$R_0=2.0/1.3/1.1$ $\delta = 0.010$ $\alpha=0.05$ $\theta=0.1$ $\%\text{Infect}=6/6/8$

DATA THROUGH 11-SEP-2020

$\theta = 0.07$
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)
Italy: Daily Deaths, Actual and Smoothed

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

Italy: Delta $d$

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

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