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

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Extended results for Italy
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:
  - 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)
Italy: Daily Deaths per Million People

Italy

Daily deaths per million people

Mar Apr May Jun Jul Aug 2020

2 4 6 8 10 12 14 16

-2

Mar Apr May Jun Jul Aug 2020
Italy: 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)
Italy: Estimates of $R_0(t)$

$R_0(t)$

Italy
$
\delta = 0.010 \quad \theta=0.10 \quad \gamma=0.20$

Mar Apr May Jun Jul Aug Sep 2020

0 0.5 1 1.5 2 2.5 3 3.5

$R_0(t)$
Italy: Percent Currently Infectious

Peak I/N = 0.74%  Final I/N = 0.00%  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 ($\alpha = .05$)

Italy

$R_0 = 2.0/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 6/6/6$

DATA THROUGH 24-AUG-2020
Italy (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

Italy

$R_0=2.0/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 6/ 6/ 6

DATA THROUGH 24-AUG-2020
Italy (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0.05$)

Italy

$R_0 = 2.0/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%Infect = 6/6/6$

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2020
Robustness to Mortality Rate, $\delta$
Italy: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

$R_0=2.0/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 6/ 6/ 6

DATA THROUGH 24-AUG-2020
Italy: Daily Deaths per Million People (\(\delta = 0.01/0.008/0.012\))

\[ R_0 = 2.0/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6 \]

DATA THROUGH 24-AUG-2020
Italy: Cumulative Deaths per Million (δ = .01/.008/.012)

DATA THROUGH 24-AUG-2020

Italy

$R_0=2.0/1.0/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 6/6/6$

$\delta = 0.008$
Reopening and Herd Immunity

– Black: assumes $R_0(\text{today})$ remains in place forever
– Red: assumes $R_0(\text{suppress}) = 1/s(\text{today})$
– 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
Italy: Re-Opening ($\alpha = 0.05$)

$$R_0(t) = 1.0, \quad R_0(\text{suppress}) = 1.1, \quad R_0(25/50) = 1.3/1.5, \quad \delta = 0.010, \quad \alpha = 0.05$$
Italy: Re-Opening ($\alpha = 0$)

$$R_0(t)=1.0, \quad R_0(\text{suppress})=1.1, \quad R_0(25/50)=1.3/1.5, \quad \delta = 0.010, \quad \alpha=0.00$$
Results for alternative parameter values
Italy (7 days): Daily Deaths per Million People ($\alpha = 0$)

Italy

$R_0=2.0/1.0/1.0 \quad \delta = 0.010 \quad \alpha=0.00 \quad \theta=0.1 \quad \%\text{Infect}= 6/6/6$

DATA THROUGH 24-AUG-2020
Italy (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

$R_0 = 2.0/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 6/6/6$

DATA THROUGH 24-AUG-2020
Italy (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

$R_0 = 2.0/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$Infect = $6/6/6$
Italy: Daily Deaths per Million People ($\delta = 0.8\%$)

Italy

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

$R_0 = 2.0/1.1/1.1 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 7/7/7$
Italy: Daily Deaths per Million People ($\delta = 1.2\%$)

Italy

$R_0 = 2.0/1.0/1.0$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 5/5/5
Italy: Cumulative Deaths per Million ($\delta = 1.2\%$)

Italy

$R_0=2.0/1.0/1.0$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  %Infect= 5/ 5/ 5
Italy: Daily Deaths per Million People ($\gamma = .2/.15$)

$R_0 = 2.0/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 6/6/6$

DATA THROUGH: 24-AUG-2020
Italy: Cumulative Deaths per Million $\gamma = .2/.15$)

$R_0=2.0/1.0/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect = 6/6/6

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2020
Italy: Daily Deaths per Million People ($\theta = .1/.07/.2$)

$R_0 = 2.0/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 6/6/6$

DATA THROUGH 24-AUG-2020
Italy: Cumulative Deaths per Million People ($\theta = .1 / .07 / .2$)

Italy

$R_0 = 2.0/1.0/1.0$  \ $\delta = 0.010$  \ $\alpha = 0.05$  \ $\theta = 0.1$  \ %Infect = 6/6/6

DATA THROUGH 24-AUG-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)
Italy: Daily Deaths, Actual and Smoothed

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