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

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Extended results for Portugal
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:
  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)
Portugal: Daily Deaths per Million People
Portugal: 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)
Portugal: Estimates of $R_0(t)$

Portugal

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

Peak I/N = 0.17%  Final I/N = 0.02%  δ= 0.010  θ=0.10  γ=0.20
Portugal: 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 $\alpha = 0$)
Portugal (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

$R_0=1.5/1.1/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=2/2/2$

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

$R_0 = 1.5/1.1/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 2/2/2$

Data through 11-Sep-2020
Portugal (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = .05$)

Portugal

$R_0=1.5/1.1/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$Infect= 2/2/2

Cumulative deaths per million people
Robustness to Mortality Rate, $\delta$
Portugal: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Portugal

$R_0 = 1.5/1.1/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}= 2/ 2/ 2$

Data through 11-Sep-2020
Portugal: Daily Deaths per Million People ($\delta = .01 / .008 / .012$)

$R_0 = 1.5 / 1.1 / 1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect $= 2 / 2 / 2$

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

Portugal

$R_0=1.5/1.1/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infected}= 2/2/2$

DATA THROUGH 11-SEP-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
Portugal: Re-Opening ($\alpha = .05$)

Portugal

$R_0(t)=1.1, \ R_0(\text{suppress})=1.0, \ R_0(25/50)=1.3/1.5, \ \delta = 0.010, \ \alpha=0.05$

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

Portugal

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

DATA THROUGH 11-SEP-2020

Portugal

$R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 2/2/3$
Portugal (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

\[ R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%Infect = 2/2/3 \]

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

Portugal

$R_0 = 1.5/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect = 2/2/3

New York City

Italy
Portugal: Daily Deaths per Million People ($\delta = 0.8\%$)

$R_0 = 1.5/1.1/1.1 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 2/2/3$
Portugal: Daily Deaths per Million People ($\delta = 1.2\%$)

Portugal

$R_0=1.5/1.1/1.0 \quad \delta = 0.012 \quad \theta=0.1 \quad \gamma=0.2 \quad \%\text{Infect}= 2/2/2$
Portugal: Cumulative Deaths per Million ($\delta = 1.2\%$)

Portugal

$R_0 = 1.5/1.1/1.0$  \  $\delta = 0.012$  \  $\theta = 0.1$  \  $\gamma = 0.2$  \  $\%\text{Infect} = 2/2/2$
Portugal: Daily Deaths per Million People ($\gamma = .2/.15$)

Portugal

$R_0 = 1.5/1.1/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 2/2/2

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

Portugal

$R_0 = 1.5/1.1/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\% \text{Infect} = 2/2/2$

DATA THROUGH 11-SEP-2020

$\gamma = 0.2$

$\gamma = 0.15$
Portugal: Daily Deaths per Million People ($\theta = .1 / .07 / .2$)

Portugal

$R_0 = 1.5/1.1/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 2/2/2$

DATA THROUGH 11-SEP-2020
Portugal: Cumulative Deaths per Million People ($\theta = .1/0.07/0.2$)

Portugal

$R_{0} = 1.5/1.1/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 2/2/2$

DATA THROUGH 11-SEP-2020

Cumulative deaths per million people

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

Portugal: Daily deaths, d
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Portugal: Change in Smoothed Daily Deaths

Portugal: Delta $d$

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

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