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

Jesús Fernández-Villaverde and Chad Jones

Extended results for Saudi Arabia
Based on data through October 9, 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)
Saudi Arabia: Daily Deaths per Million People

Saudi Arabia

Daily deaths per million people

Apr May Jun Jul Aug Sep Oct

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
Saudi Arabia: 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)
Saudi Arabia: Estimates of $R_0(t)$

Saudi Arabia

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
Saudi Arabia: Percent Currently Infectious

Saudi Arabia
Peak I/N = 0.07%  Final I/N = 0.04%  δ = 0.010  θ = 0.10  γ = 0.20
Saudi Arabia: 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 $\alpha = 0$)
Saudi Arabia (7 days): Daily Deaths per Million People ($\alpha = .05$)

Saudi Arabia

$R_0 = 1.3/0.9/1.0 \; \delta = 0.010 \; \alpha = 0.05 \; \theta = 0.1 \; \%\text{Infect} = 1/2/2$

DATA THROUGH 09-OCT-2020
Saudi Arabia (7 days): Cumulative Deaths per Million (Future, $\alpha = 0.05$)

Saudi Arabia

$R_0 = 1.3/0.9/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infected = 1/2/2

DATA THROUGH 09-OCT-2020
Saudi Arabia (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0.05$).

Saudi Arabia
$R_0 = 1.3/0.9/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $%\text{Infect} = 1/2/2$

New York City

Italy
Robustness to Mortality Rate, $\delta$
Saudi Arabia: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Saudi Arabia

$R_0=1.3/0.9/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 1/ 2/ 2

DATA THROUGH 09-OCT-2020
Saudi Arabia: Daily Deaths per Million People ($\delta = 0.01/0.008/0.012$)

Saudi Arabia

$R_0 = 1.3/0.9/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%Infect = 1/2/2$

DATA THROUGH 09-OCT-2020
Saudi Arabia: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Saudi Arabia

$R_0 = 1.3/0.9/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect = 1/2/2

DATA THROUGH 09-OCT-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
Saudi Arabia: Re-Opening ($\alpha = .05$)

Saudi Arabia

$R_0(t)=0.9, \ R_0(suppress)=1.0, \ R_0(25/50)=1.2/1.5, \ \delta = 0.010, \ \alpha=0.05$

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

Saudi Arabia

$R_0(t) = 0.9$, $R_0(\text{suppress}) = 1.0$, $R_0(25/50) = 1.2/1.5$, $\delta = 0.010$, $\alpha = 0.00$

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

Saudi Arabia

$R_0=1.3/0.9/0.9 \; \delta = 0.010 \; \alpha=0.00 \; \theta=0.1 \; \%Infect=1/2/2$

DATA THROUGH 09-OCT-2020
Saudi Arabia (7 days): Cumulative Deaths per Million (Future, $\alpha = 0$)

Saudi Arabia

$R_0 = 1.3/0.9/0.9$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  %Infect $= 1/2/2$

DATA THROUGH 09-OCT-2020
Saudi Arabia (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

Saudi Arabia

$R_0 = 1.3 / 0.9 / 0.9$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$Infect = 1 / 2 / 2
Saudi Arabia: Daily Deaths per Million People ($\delta = 0.8\%$)
Saudi Arabia: Cumulative Deaths per Million ($\delta = 0.8\%$)

Saudi Arabia

$R_0 = 1.3/0.9/1.0$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect = 2/2/2
Saudi Arabia: Daily Deaths per Million People ($\delta = 1.2\%$)

Saudi Arabia

$R_0=1.3/0.9/1.0$  $\delta = 0.012$  $\theta=0.1$  $\gamma=0.2$  $%\text{Infect} = 1/1/2$
Saudi Arabia: Cumulative Deaths per Million ($\delta = 1.2\%$)

Saudi Arabia

$R_0 = 1.3/0.9/1.0$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%Infect = 1/1/2$
Saudi Arabia: Daily Deaths per Million People (γ = .2/.15)

Saudi Arabia

$R_0 = 1.3/0.9/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 1/2/2

DATA THROUGH 09-OCT-2020
Saudi Arabia: Cumulative Deaths per Million $\gamma = 0.2/0.15$)

Saudi Arabia

$R_0=1.3/0.9/1.0 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=1/2/2$

$\gamma \equiv 0.75$

DATA THROUGH 09-OCT-2020
Saudi Arabia: Daily Deaths per Million People ($\theta = .1/.07/.2$)

Saudi Arabia

$R_0 = 1.3/0.9/1.0 \ \ \delta = 0.010 \ \ \alpha = 0.05 \ \ \theta = 0.1 \ \ %\text{Infect} = 1/2/2$

DATA THROUGH 09-OCT-2020

Daily deaths per million people

Saudi Arabia: Cumulative Deaths per Million People ($\theta = 0.1 / 0.07 / 0.2$)

Saudi Arabia

$R_0 = 1.3 / 0.9 / 1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 1 / 2 / 2

DATA THROUGH 09-OCT-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)
Saudi Arabia: Daily Deaths, Actual and Smoothed

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

Δd = 0.010  θ=0.10  γ=0.20
Saudi Arabia: Change in (Change in Smoothed Daily Deaths)

Saudi Arabia: Delta (Δd)

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