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

Jesús Fernández-Villaverde and Chad Jones

Extended results for New York City (plus)
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)
New York City (plus): Daily Deaths per Million People

Daily deaths per million people

Apr May Jun Jul Aug 2020
New York City (plus): 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)
New York City (plus): Estimates of $R_0(t)$

- $\delta = 0.010$
- $\theta = 0.10$
- $\gamma = 0.20$

The diagram shows the estimated values of $R_0(t)$ for New York City (plus) from March to September 2020.
New York City (plus): Percent Currently Infectious

New York City (plus)
Peak I/N = 4.27%  Final I/N = 0.02%  δ = 0.010  θ = 0.10  γ = 0.20
New York City (plus): 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:

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

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

     $R_0$ 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 $\alpha = 0$)
New York City (plus) (7 days): Daily Deaths per Million People ($\alpha = 0.05$)

Daily deaths per million people

DATA THROUGH 24-AUG-2020

New York City (plus)

$R_0 = 2.3/1.1/1.1$  \(\delta = 0.010\)  \(\alpha = 0.05\)  \(\theta = 0.1\)  \%Infect = 24/24/24
New York City (plus) (7 days): Cumulative Deaths per Million (Future, α)

New York City (plus)

$R_0 = 2.3/1.1/1.1\quad \delta = 0.010\quad \alpha = 0.05\quad \theta = 0.1\quad %\text{Infect}=24/24/24$

DATA THROUGH 24-AUG-2020
New York City (plus) (7 days): Cumulative Deaths per Million, Log Scale

New York City (plus)
$R_0 = 2.3/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 24/24/24$
Robustness to Mortality Rate, $\delta$
New York City (plus): Cumulative Deaths per Million ($\delta = .01/.008/.012$)

New York City (plus)

$R_0 = 2.3/1.1/1.1 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=24/24/24$

DATA THROUGH 24-AUG-2020
New York City (plus): Daily Deaths per Million People ($\delta = .01/.008/.012$)

\[ R_0 = 2.3/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 24/24/24 \]
New York City (plus): Cumulative Deaths per Million ($\delta = .01/.008/.012$)

DATA THROUGH 24-AUG-2020

New York City (plus)

$R_0 = 2.3/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%Infect = 24/24/24$

Cumulative deaths per million people
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
New York City (plus): Re-Opening ($\alpha = .05$)

New York City (plus)

$R_0(t)=1.1$, $R_0(suppress)=1.3$, $R_0(25/50)=1.4/1.7$, $\delta = 0.010$, $\alpha=0.05$
New York City (plus): Re-Opening ($\alpha = 0$)

New York City (plus)

$R_0(t)=1.1$, $R_0(\text{suppress})=1.3$, $R_0(25/50)=1.4/1.7$, $\delta = 0.010$, $\alpha=0.00$
Results for alternative parameter values
New York City (plus) (7 days): Daily Deaths per Million People ($\alpha = 0$)

New York City (plus)

$R_0 = 2.3/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect}=24/24/24$

DATA THROUGH 24-AUG-2020
New York City (plus) (7 days): Cumulative Deaths per Million (Future, $\alpha$)

New York City (plus)
$R_0=2.3/1.1/1.1 \quad \delta = 0.010 \quad \alpha=0.00 \quad \theta=0.1 \quad \%\text{Infect}=24/24/24$

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2020
New York City (plus) (7 days): Cumulative Deaths per Million, Log Scale

New York City (plus)

$R_0 = 2.3/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$ Infect = 24/24/24
New York City (plus): Daily Deaths per Million People ($\delta = 0.8\%$)

New York City (plus)
$R_0 = 2.3/1.2/1.2 \quad \delta = 0.008 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 30/30/30$
New York City (plus): Cumulative Deaths per Million ($\delta = 0.8\%$)

New York City (plus)

$R_0 = 2.3/1.2/1.2$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%\text{Infect} = 30/30/30$
New York City (plus): Daily Deaths per Million People \((\delta = 1.2\%)\)

New York City (plus)
\[ R_0 = 2.3/1.0/1.0 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%\text{Infect} = 20/20/20 \]
New York City (plus): Cumulative Deaths per Million ($\delta = 1.2\%$)

New York City (plus)
$R_0=2.3/1.0/1.0$  $\delta=0.012$  $\theta=0.1$  $\gamma=0.2$  $\%\text{Infect}=20/20/20$
New York City (plus): Daily Deaths per Million People ($\gamma = 0.2/0.15$)

New York City (plus)

$R_0 = 2.3/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}=24/24/24$

DATA THROUGH 24-AUG-2020
New York City (plus): Cumulative Deaths per Million $\gamma = .2/.15$

New York City (plus)
$R_0 = 2.3/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%\text{Infect} = 24/24/24$

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

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

New York City (plus)

$R_0 = 2.3/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$Infect$=24/24/24$

DATA THROUGH 24-AUG-2020
New York City (plus): Cumulative Deaths per Million People ($\theta = .1/.07/1.07$)

New York City (plus)

$R_0 = 2.3/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 24/24/24$
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)
New York City (plus): Daily Deaths, Actual and Smoothed

New York City (plus): Daily deaths, $d$

$$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$$
New York City (plus): Change in Smoothed Daily Deaths

\[
\delta = 0.010 \quad \theta=0.10 \quad \gamma=0.20
\]
New York City (plus): Change in (Change in Smoothed Daily Deaths)

New York City (plus): Delta (Delta d)
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]