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

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

Daily deaths per million people
**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: Estimates of $R_0(t)$

New York

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

March Apr May Jun Jul Aug Sep 2020
New York: Percent Currently Infectious

Percent currently infectious, I/N (percent)

Peak I/N = 2.84%  Final I/N = 0.01%  δ = 0.010  β = 0.10  γ = 0.20
New York: Growth Rate of Daily Deaths over Past Week (percent)

New York
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
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 $R_0(t) = \text{final empirical value}$. 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 $\alpha = 0.05$ (see robustness section for $\alpha = 0$)
New York (7 days): Daily Deaths per Million People ($\alpha = .05$)

New York

$R_0 = 2.3/0.8/0.9$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infections = 17/17/17

DATA THROUGH 24-AUG-2020
New York (7 days): Cumulative Deaths per Million (Future, $\alpha = 0.05$)

New York
$R_0=2.3/0.8/0.9 \hspace{1em} \delta = 0.010 \hspace{1em} \alpha=0.05 \hspace{1em} \theta=0.1 \hspace{1em} \%\text{Infect}=17/17/17$

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

New York

\(R_0 = 2.3/0.8/0.9\)  \(\delta = 0.010\)  \(\alpha = 0.05\)  \(\theta = 0.1\)  \%Infect = 17/17/17
Robustness to Mortality Rate, $\delta$
New York: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

New York

$R_0 = 2.3/0.8/0.9$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 17/17/17

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

New York

$R_0 = 2.3/0.8/0.9$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 17/17/17$

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

New York

$R_0=2.3/0.8/0.9 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=17/17/17$

DATA THROUGH 24-AUG-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 $R_0 = \text{“normal”}$
– **Purple**: we move 50% of the way from $R_0(today)$ back to initial $R_0 = \text{“normal”}$

**NOTE**: Lines often cover each other up
New York: Re-Opening ($\alpha = .05$)

New York

$R_0(t)=0.8$, $R_0(\text{suppress})=1.2$, $R_0(25/50)=1.2/1.6$, $\delta = 0.010$, $\alpha=0.05$
New York: Re-Opening ($\alpha = 0$)

New York

$R_0(t)=0.8, \ R_0\text{(suppress)}=1.2, \ R_0(25/50)=1.2/1.6, \ \delta = 0.010, \ \alpha=0.00$
Results for alternative parameter values
New York (7 days): Daily Deaths per Million People ($\alpha = 0$)

New York

$R_0 = 2.3/0.8/0.8$  \hspace{1em} $\delta = 0.010$  \hspace{1em} $\alpha = 0.00$  \hspace{1em} $\theta = 0.1$  \hspace{1em} %Infect = 17/17/17

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

New York

$R_0 = 2.3/0.8/0.8 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect}=17/17/17$

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2020
New York (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

New York

$R_0 = 2.3 / 0.8 / 0.8$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$ Infect = 17/17/17
New York: Daily Deaths per Million People ($\delta = 0.8\%$)

New York

$R_0 = 2.3/0.9/0.9$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$ Infect $= 21/21/21$
New York: Cumulative Deaths per Million ($\delta = 0.8\%$)

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New York
$R_0=2.3/0.9/0.9 \quad \delta = 0.008 \quad \theta=0.1 \quad \gamma=0.2 \quad \%Infect=21/21/21$
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New York: Daily Deaths per Million People ($\delta = 1.2\%$)

New York

$R_0 = 2.3/0.8/0.8$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  %Infect = 14/14/14
New York: Cumulative Deaths per Million ($\delta = 1.2\%$)

New York

$R_0 = 2.3/0.8/0.8$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect$=14/14/14$
New York: Daily Deaths per Million People ($\gamma = 0.2/0.15$)

New York

$R_0 = 2.3/0.8/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 17/17/17$

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

New York

$R_0=2.3/0.8/0.9 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad \%\text{Infect}=17/17/17$

DATA THROUGH 24-AUG-2020

$\gamma = 0.25$
New York: Daily Deaths per Million People ($\theta = 0.1 / 0.07 / 0.2$)

New York

$R_0 = 2.3 / 0.8 / 0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect}=17/17/17$

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

New York

$R_0 = 2.3/0.8/0.9 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 17/17/17$

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)
New York: Daily Deaths, Actual and Smoothed

New York: Daily deaths, $d$

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

New York: $\Delta d$

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
New York: Delta (Δd)

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