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

Jesús Fernández-Villaverde and Chad Jones

Extended results for Boston+Middlesex
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)
Boston+Middlesex: Daily Deaths per Million People

![Graph showing daily deaths per million people in Boston+Middlesex from April to October 2020. The graph displays a significant spike in deaths during May, with a gradual decrease thereafter.](image-url)
Boston+Middlesex: 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)
Boston+Middlesex: Estimates of $R_0(t)$

$\delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20$
Boston+Middlesex: Percent Currently Infectious

Boston+Middlesex
Peak I/N = 1.77%   Final I/N = 0.08%   $\delta=0.010$   $\theta=0.10$   $\gamma=0.20$
Boston+Middlesex: 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 $\alpha = 0$)
Boston+Middlesex (7 days): Daily Deaths per Million People $\left(\alpha = .05\right)$

Boston+Middlesex

$R_0=2.1/1.1/1.1 \quad \delta = 0.010 \quad \alpha=0.05 \quad \theta=0.1 \quad %Ifect=14/14/15$

DATA THROUGH 09-OCT-2020
Boston+Middlesex (7 days): Cumulative Deaths per Million (Future, $\alpha = 1.1$)

$R_0 = 2.1/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 14/14/15$

DATA THROUGH 09-OCT-2020
Boston+Middlesex (7 days): Cumulative Deaths per Million, Log Scale

New York City

Italy

Boston+Middlesex

$R_0 = 2.1/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect}=14/14/15$
Robustness to Mortality Rate, $\delta$
Boston+Middlesex: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Boston+Middlesex

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 14/14/15

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

Boston+Middlesex

$R_0 = 2.1/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 14/14/15$

DATA THROUGH 09-OCT-2020
Boston+Middlesex: Cumulative Deaths per Million (δ = .01/.008/.012)

Boston+Middlesex

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect=14/14/15

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
Boston+Middlesex: Re-Opening \( (\alpha = .05) \)

Boston+Middlesex

\[ R_0(t) = 1.1, \quad R_0(\text{suppress}) = 1.2, \quad R_0(25/50) = 1.3/1.6, \quad \delta = 0.010, \quad \alpha = 0.05 \]

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

Boston+Middlesex

$R_0(t)=1.0$, $R_0$ (suppress) = 1.2, $R_0(25/50)=1.3/1.6$, $\delta = 0.010$, $\alpha = 0.00$
Results for alternative parameter values
Boston+Middlesex (7 days): Daily Deaths per Million People ($\alpha = 0$)

R$_0$=2.1/1.0/1.0  $\delta = 0.010$  $\alpha=0.00$  $\theta=0.1$  %Infect=14/14/14

DATA THROUGH 09-OCT-2020
Boston+Middlesex (7 days): Cumulative Deaths per Million (Future, $\alpha = 2.1$)

$R_0 = 2.1/1.0/1.0 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad %\text{Infect}=14/14/14$

DATA THROUGH 09-OCT-2020
Boston+Middlesex (7 days): Cumulative Deaths per Million, Log Scale

Boston+Middlesex

$R_0 = 2.1/1.0/1.0$  $\delta = 0.010$  $\alpha = 0.00$  $\theta = 0.1$  $\%$Infect = 14/14/14
Boston+Middlesex: Daily Deaths per Million People ($\delta = 0.8\%$)

Boston+Middlesex

$R_0 = 2.1/1.1/1.2$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%\text{Infect} = 17/18/18$
Boston+Middlesex: Cumulative Deaths per Million ($\delta = 0.8\%$)

Boston+Middlesex

$R_0 = 2.1/1.1/1.2$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect = 17/18/18
Boston+Middlesex: Daily Deaths per Million People \( (\delta = 1.2\%) \)

Boston+Middlesex

\[ R_0=2.1/1.0/1.1 \quad \delta = 0.012 \quad \theta=0.1 \quad \gamma=0.2 \quad \%\text{Infect}=12/12/12 \]
Boston+Middlesex: Cumulative Deaths per Million ($\delta = 1.2\%$)

Boston+Middlesex

$R_0=2.1/1.0/1.1 \quad \delta = 0.012 \quad \theta=0.1 \quad \gamma=0.2 \quad \%\text{Infect}=12/12/12$
Boston+Middlesex: Daily Deaths per Million People ($\gamma = .2/ .15$)

Boston+Middlesex

$R_0 = 2.1/1.1/1.1$  \( \delta = 0.010 \)  \( \alpha = 0.05 \)  \( \theta = 0.1 \)  \%Infect = 14/14/15
Boston+Middlesex: Cumulative Deaths per Million $\gamma = 0.2 / 0.15$)

Boston+Middlesex

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  %Infect = 14/14/15

DATA THROUGH 09-OCT-2020

Cumulative deaths per million people


$\gamma = 0.2$

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

Boston+Middlesex

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%Infect = 14/14/15$

DATA THROUGH 09-OCT-2020
Boston+Middlesex: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

Boston+Middlesex

$R_0 = 2.1/1.1/1.1$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect=14/14/15

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)
Boston+Middlesex: Daily Deaths, Actual and Smoothed

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

Boston+Middlesex: Delta $d$

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

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