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

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Extended results for Missouri
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)
Missouri: 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)
Missouri: Estimates of $R_0(t)$

Missouri
\[ \delta = 0.010 \quad \theta = 0.10 \quad \gamma = 0.20 \]
Missouri: Percent Currently Infectious

Missouri
Peak I/N = 0.16%  Final I/N = 0.09%  $\delta = 0.010$  $\theta = 0.10$  $\gamma = 0.20$
Missouri: Growth Rate of Daily Deaths over Past Week (percent)

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

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

     \[
     \Rightarrow \alpha \approx 0.05
     \]

     $R_0$ 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 $\alpha = 0$)
Missouri (7 days): Daily Deaths per Million People ($\alpha = .05$)

Missouri

$R_0 = 1.5/1.1/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \%\text{Infect} = 3/3/5$

DATA THROUGH 24-AUG-2020
Missouri (7 days): Cumulative Deaths per Million (Future, $\alpha = .05$)

Missouri

$R_0=1.5/1.1/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \% \text{Infect} = 3/3/5$

DATA THROUGH 24-AUG-2020

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec 2020
Missouri (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0.05$)

Missouri

$R_0=1.5/1.1/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%\text{Infect}= 3/3/5$
Robustness to Mortality Rate, $\delta$
Missouri: Cumulative Deaths per Million ($\delta = .01/.008/.012$)

Missouri

$R_0=1.5/1.1/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  %Infect= 3/3/5

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

Missouri

$R_0 = 1.5/1.1/1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%Infect = 3/3/5$

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

Missouri

\(R_0 = 1.5/1.1/1.0\) \(\delta = 0.010\) \(\alpha = 0.05\) \(\theta = 0.1\) \(\%\text{Infect} = 3/3/5\)

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 $R_0 = “normal”$
– Purple: we move 50% of the way from $R_0(today)$ back to initial $R_0 = “normal”$

NOTE: Lines often cover each other up
Missouri: Re-Opening ($\alpha = 0.05$)

Missouri

$R_0(t)=1.1$, $R_0\text{(suppress)}=1.0$, $R_0(25/50)=1.3/1.5$, $\delta = 0.010$, $\alpha=0.05$
Missouri: Re-Opening ($\alpha = 0$)

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

Missouri

\[ R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 3/3/7 \]

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

Missouri

$R_0 = 1.5/1.1/1.1\quad \delta = 0.010\quad \alpha = 0.00\quad \theta = 0.1\quad \%\text{Infect} = 3/3/7$

DATA THROUGH 24-AUG-2020
Missouri (7 days): Cumulative Deaths per Million, Log Scale ($\alpha = 0$)

Missouri

$R_0 = 1.5/1.1/1.1 \quad \delta = 0.010 \quad \alpha = 0.00 \quad \theta = 0.1 \quad \%\text{Infect} = 3/3/7$

New York City

Italy

Cumulative deaths per million people

Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan

2020
Missouri: Cumulative Deaths per Million ($\delta = 0.8\%$)

Missouri

$R_0 = 1.5/1.1/1.1$  $\delta = 0.008$  $\theta = 0.1$  $\gamma = 0.2$  $\%Infect = 3/4/6$
Missouri: Daily Deaths per Million People ($\delta = 1.2\%$)

Missouri

$R_0 = 1.5/1.1/1.0 \quad \delta = 0.012 \quad \theta = 0.1 \quad \gamma = 0.2 \quad \%Infect = 2/3/4$
Missouri: Cumulative Deaths per Million ($\delta = 1.2\%$)

Missouri

$R_0 = 1.5/1.1/1.0$  $\delta = 0.012$  $\theta = 0.1$  $\gamma = 0.2$  $\%$Infect $= 2/3/4$
Missouri: Daily Deaths per Million People ($\gamma = .2/.15$)

Missouri

$R_0=1.5/1.1/1.0$  $\delta = 0.010$  $\alpha=0.05$  $\theta=0.1$  $\%$ Infect= 3/ 3/ 5

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

Missouri

$R_0 = 1.5 / 1.1 / 1.0$  $\delta = 0.010$  $\alpha = 0.05$  $\theta = 0.1$  $\%$ Infect $= 3 / 3 / 5$

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

Missouri

$R_0=1.5/1.1/1.0\, \delta = 0.010\, \alpha=0.05\, \theta=0.1\, \%\text{Infect} = 3/3/5$

DATA THROUGH 24-AUG-2020

![Graph showing daily deaths per million people in Missouri from April to December 2020. The graph includes a line chart with data points for each month, indicating the number of daily deaths per million people. The chart shows a peak in deaths in May and a decline towards August, with a slight increase in September and October.](image-url)
Missouri: Cumulative Deaths per Million People ($\theta = .1/.07/.2$)

\[ R_0 = 1.5/1.1/1.0 \quad \delta = 0.010 \quad \alpha = 0.05 \quad \theta = 0.1 \quad \% \text{Infect} = 3/3/5 \]

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)
Missouri: Daily Deaths, Actual and Smoothed

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

Missouri: Delta $d$

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

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