Estimating the number of infections and the impact of non-pharmaceutical interventions on COVID-19


ECMI’2020-math4covid
Motivation

- COVID-19 emerged in Europe, from January or latter.
- Various governments have implemented various control measures to stop the spread
- Need to estimate the effectiveness of interventions
- Estimation of time varying reproduction is challenging, due to
  - High proportion of infections not detected by health systems
  - Regular change in testing policies
  - Most health systems have capacity to test only `high risk` cases
- Estimation based on reported cases is systematically biased
- Use a more reliable source observed deaths, and use it to back-calculate the infections. Hence, the reproduction numbers.
Model Components

- Observed deaths
- Modelled deaths
- Modelled infections
- Basic reproduction number
- Time varying reproduction number
- Symptoms to death distribution
- Serial interval distribution
- Population averaged infection fatality ratio
- Infection to symptoms distribution
- Country specific interventions
- Effects shared for all countries
  - Social distancing encouraged
  - Close schools or universities
  - Case based isolation
  - Banning public events
  - Onset of first intervention
  - Lockdown
Bayesian Semi Mechanistic Model: Death Model

\[ D_{t,m} \sim \text{Negative Binomial} \left( d_{t,m}, d_{t,m} + \frac{d_{t,m}^2}{\psi} \right) \]

\[ \psi \sim \mathcal{N}^+(0, 5) \]

\[ifr_m^* \sim ifr_m \cdot \mathcal{N}(1, 0.1)\]

\[\pi \sim \text{Gamma}(5.1, 0.86) + \text{Gamma}(17.8, 0.45)\]

\[d_{t,m} = ifr_m^* \sum_{\tau=0}^{t-1} c_{\tau,m} \pi^{t-\tau}\]
Renewal equation

\[
c_{t,m} = S_{t,m} R_{t,m} \sum_{\tau=0}^{t-1} c_{\tau,m} g_{t-\tau}
\]

\[
S_{t,m} = 1 - \frac{\sum_{i=1}^{t-1} c_{i,m}}{N_m}
\]

\[
g \sim \text{Gamma}(6.5, 0.62)
\]
Bayesian Semi Mechanistic Model: Reproduction Number

\[ R_{t,m} = R_{0,m} e^{-\sum_{k=1}^{6} \alpha_k I_{k,t,m} - \beta_m I_{5,t,m}} \]

\[ R_{0,m} \sim \mathcal{N}^+(3.28, |\kappa|) \]

\[ \alpha_k \sim \text{Gamma}(1/6, 1) - \frac{\log(1.05)}{6} \]

\[ \beta_1, \ldots, \beta_M \sim N(0, \gamma) \text{ where } \gamma \sim \mathcal{N}^+(0, .2) \]
Interventions

- Case based self isolation mandated
- Social distancing encouraged
- Public events banned
- School closure ordered
- Lockdown ordered

MARCH 2020
Results

United Kingdom

Sweden

Interventions
- Complete lockdown
- Public events banned
- School closure
- Self isolation
- Social distancing encouraged

[50% 95%]
## Results: Percentage Infected

<table>
<thead>
<tr>
<th>Country</th>
<th>% of total population infected (mean [95% credible interval])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>0.81% [0.62%-1.07%]</td>
</tr>
<tr>
<td>Belgium</td>
<td>10.97% [7.85%-15.17%]</td>
</tr>
<tr>
<td>Denmark</td>
<td>0.93% [0.69%-1.24%]</td>
</tr>
<tr>
<td>France</td>
<td>3.87% [2.94%-5.05%]</td>
</tr>
<tr>
<td>Germany</td>
<td>0.84% [0.63%-1.09%]</td>
</tr>
<tr>
<td>Greece</td>
<td>0.13% [0.10%-0.17%]</td>
</tr>
<tr>
<td>Italy</td>
<td>4.38% [3.52%-5.47%]</td>
</tr>
<tr>
<td>Netherlands</td>
<td>3.27% [2.53%-4.24%]</td>
</tr>
<tr>
<td>Norway</td>
<td>0.52% [0.38%-0.71%]</td>
</tr>
<tr>
<td>Portugal</td>
<td>1.11% [0.85%-1.49%]</td>
</tr>
<tr>
<td>Spain</td>
<td>5.34% [4.19%-6.86%]</td>
</tr>
<tr>
<td>Sweden</td>
<td>6.44% [3.95%-9.95%]</td>
</tr>
<tr>
<td>Switzerland</td>
<td>1.92% [1.47%-2.48%]</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>4.10% [3.12%-5.39%]</td>
</tr>
</tbody>
</table>

*Posterior model estimates of percentage of total population infected over the course of the pandemic. Estimates as of 2020-04-28.*
Estimated impact of interventions on $R_t$

Mean relative percentage reduction in $R_t$ is shown with 95% posterior credible intervals. If 100% reduction is achieved, $R_t = 0$ and there is no more transmission of COVID-19.
Results: Effectiveness of Interventions

The graph shows the cumulative number of deaths over time, comparing two models:
- Red: our model
- Blue: counterfactual

The x-axis represents time from March 1st to April 15th, with intermediate labels at March 15th and April 1st.

The y-axis represents the cumulative number of deaths, ranging from 0 to 1,000,000.
Summary

- Semi-mechanistic Bayesian hierarchical model to attempt to infer the impact of these interventions across 11 European countries.
- We estimate that countries have managed to reduce their reproduction number substantially.
- The proportion of the population infected to date – the attack rate - is estimated to be highest in Sweden and Belgium and lowest in Norway, Austria and Germany.
- Major non-pharmaceutical interventions and lockdown in particular have had a large effect on reducing transmission.
- Given the counterfactual we present it is critical that the current interventions remain in place and trends in cases and deaths are closely monitored in the coming days and weeks to provide reassurance that transmission of SARS-Cov-2 is under control.
Limitations and Assumptions

- Changes in the reproductive number – a measure of transmission - are an immediate response to interventions.
- Each intervention has the same effect on the reproduction number across countries and over time, excluding the lockdown intervention.
- For lockdown, we now estimate a global effect and a country specific effect.
- The interventions that we consider have different implementation details across countries, which we do not take into account.
- We make various further assumptions that our model results are contingent on (e.g. about the time between infections, about being able to observe all COVID-related deaths (we do have under-reporting parameter work in progress), about the time between infection and death and about the infection-fatality-ratio).
Thanks!


Website: https://mrc-ide.github.io/covid19estimates/#/

Code: https://github.com/ImperialCollegeLondon/covid19model
Sensitivity on Generation Distribution

Generation distribution mean: 5, 6.5, 7, 8

# of deaths averted

Mar 16 | Mar 23 | Mar 30 | Apr 06 | Apr 13
Sensitivity on Onset To Death Distribution