Effectiveness of travel restrictions

Abstract

The European Union closed all of them on March 17, 2020, for the first time in history. The spread of coronavirus 2019, COVID-19, is contained within its external borders. Governments across the globe have imposed unprecedented travel restrictions and border protection over the past two months to avoid the spread of this global pandemic. The exact effects of travel restrictions on COVID-19 outbreak dynamics remain unclear, however. Here, to simulate and forecast the outbreak dynamics and outbreak control of COVID-19 throughout Europe, we combine a global network mobility model with a local epidemiology model. We compare our mobility model with passenger air travel statistics and use the number of recorded COVID-19 cases for each country to calibrate our epidemiology model. Our simulations demonstrate that air travel mobility networks can predict a pandemic's evolving global diffusion trend at the early stages of the outbreak. Our findings indicate that unregulated mobility has markedly accelerated the spread of COVID-19, especially in Central Europe, Spain, and France. Ultimately, political decision making can be guided by our network epidemiology model and help define exit strategies from existing travel restrictions and complete lockdown.

Introduction

On March 13, 2020, with more confirmed cases and deaths than the rest of the world combined, the World Health Organization named Europe the epicenter of the 2019 coronavirus pandemic (World Health Organization 2020). On 24 January 2020, the first official case of COVID-19 in Europe was registered in France, followed just three and five days later by Germany and Finland. On 17 March 2020, the European Union closed all its external borders to prevent the further spread of the virus for the first time in its history (European Commission 2020). The decision to ban all non-essential travel temporarily was by no way uncontroversial, but it was very much in line with other local governments' mitigation strategies: On March 9, Italy implemented a nationwide lockout, Germany implemented school closures and border closures beginning on March 13, Spain followed on March 14, and France on March 16. More than 250 million people in Europe were in lockdown by 18 March 2020 (Wikipedia 2020). As the economic pressure to define exit strategies is growing, we wonder how successful these steps are in minimizing the spread of COVID-19 and COVID-19. How dangerous it will be to lift them?

Obviously, without the drastic political steps of increased border security and major travel bans, we'll never know exactly what would have happened. Mathematical modeling (Hsu 2020) is one possibility for estimating the efficacy of travel restrictions. Infectious disease mathematical modeling dates back to Daniel Bernoulli in 1760 (Bernoulli 1760) and has been commonly used (Kermack and McKendrick 1927) in the epidemiological community since the 1920s. The most popular approach to modeling the epidemiology of an infectious disease is to reflect through a variety of compartments the stages of the disease and incorporate constitutive relationships that define the transition between individual subpopulations (Hethcote 2000). The SEIR model is a common compartment model representing the timeline of a Disease through the interplay of populations that are susceptible, exposed, contagious, and recovered (Aron and Schwartz 1984). The transition rates α from exposed to infectious and from infectious to recovered are the inverse of the latent period $A = 1 / \alpha$ of the time during which a person is exposed but not yet infectious, and the infectious period $C = 1 / \gamma$ of the time during which a person can infect others (Li and Muldowney 1994). Both are, in principle, disease-specific parameters, regardless of nation, area, or city. For COVID-19, they will differ between A= 2 to 6 days and C= 3to 18 days, depending on the way of reporting.

Materials and Methods

Epidemiology model

We model the epidemiology of the COVID-19 outbreak using a four-compartment SEIR model, controlled by a collection of ordinary differential equations, the prone, exposed, infectious, and recovered populations (Hethcote 2000),

$$
\begin{array}{rcllll}
\dot{S} & = & -\beta S I & & & \\
\dot{E} & = & +\beta S I & - & \alpha E & \\
\dot{I} & = & & + & \alpha E & - \; \gamma I \\
\dot{R} & = & & & & + \; \gamma I \, .
\end{array}
$$

The transfer rates between the four compartments β, γ, and α are inverses of the contact period $B = 1 / \beta$, the latent period $A = 1 / \alpha$ and the infectious period $C = 1 / \gamma$ The latent and infectious periods A and C are interpreted as disease-specific and the contact period B as activity c. Using an implicit Euler backward scheme, we discretize the SEIR model in time and follow a Newton Raphson approach to solve the regular increments in each compartment.

Mobility Model

We model the spreading of COVID-19 through a mobility network of passenger air travel, which we represent as a weighted undirected graph $\mathcal{G}$ with N nodes and E edges (Peirlinck et al. 2020). The $N = 27$ nodes represent the countries of the European Union, the $E = 172$ edges the most traveled connections between them. We estimate the mobility within the graph $\mathcal{G}$ using the annual passenger air travel statistics (Eurostat 2020) from which we create the adjacency matrix, A_{IJ}, that represents the travel frequency between two countries I and J, and the degree matrix, $D_{II} = \operatorname{diag} \sum_{J=1,J\neq I}^{N} A_{IJ}$, that represents the number of incoming and outgoing passengers for each country I . The difference between the degree matrix D_{IJ} and the adjacency matrix A_{IJ} defines the weighted graph Laplacian L_{IJ},

$$L_{IJ} = D_{IJ} - A_{IJ} \,.$$

Figure 1, top left, illustrates the discrete graph $\mathcal{G}$ of the European Union with 27 nodes and 172 edges. The size and color of the nodes represent the degree D_{II}, the thickness of the edges represents the adjacency A_{IJ}. For our passenger travel-weighted graph, the degree ranges from 222 million in Germany, 221 million in Spain, 162 million in

France, and 153 million in Italy to just 4 million in Luxembourg, 3 million in Estonia and Slovakia, and 2 million in Slovenia, with a mean degree of $\bar{D}_{II} = 48 \pm 64$ million per node. We assume that the Laplacian L_{IJ}, normalized to one and scaled by the mobility coefficient ϑ, characterizes the global spreading of COVID-19. We discretize our SEIR model on our weighted graph $\mathcal{G}$ and introduce the susceptible, exposed, infectious, and recovered populations S_I, E_I, I_I, and R_I as global unknowns at the $I = 1, ..., N$ nodes of the graph $\mathcal{G}$. This results in the spatial discretization of the set of equations with $4\,N$ unknowns,

$$\begin{aligned}
\dot{S}_I &= - \textstyle\sum_{J=1}^{N} \vartheta\, L_{IJ}\, S_J - \beta\, S\, I \\
\dot{E}_I &= - \textstyle\sum_{J=1}^{N} \vartheta\, L_{IJ}\, E_J + \beta\, S\, I - \alpha\, E \\
\dot{I}_I &= - \textstyle\sum_{J=1}^{N} \vartheta\, L_{IJ}\, I_J \qquad\qquad + \alpha\, E - \gamma\, I \\
\dot{R}_I &= - \textstyle\sum_{J=1}^{N} \vartheta\, L_{IJ}\, R_J \qquad\qquad\qquad\quad + \gamma\, I \,.
\end{aligned}$$

We discretize our SEIR network model in time using an implicit Euler backward scheme and adopt a Newton Raphson method to solve for the daily increments in each compartment in each country (Fornari et al. 2019).

Result

In an effort to postpone the outbreak of the pandemic, results support the decision of the European Union and its local governments to introduce stringent travel restrictions. For example, Austria has rapidly adopted drastic mitigation measures, including tight border protection and major travel prohibitions. By 20 March, national air traffic had been halved and shortly thereafter converted to a drop of 95% (Eurostat 2020). This has steadily decreased the number of new cases to a current 10% fraction.

In Figure 3, our prognosis for Austria indicates that Austria will still see an increase in the infected population without travel restrictions. Critics claim that interventions such as physical distance, touch tracing, and isolation focused on community-based public health will be equally effective, but less restrictive, alternatives to limiting freedom of movement (Mason Meier et al. 2020). We are currently refining our model in order to change the model dynamically. The amount of replication and its modifications are linked to the timing and severity of political behavior.