The effect of travel restrictions on the spread of a highly contagious disease in Sweden

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Abstract

Travel restrictions may reduce the spread of a contagious disease that threatens public health. In this study we investigate what effect different levels of travel restrictions may have on the speed and geographical spread of an outbreak of a disease similar to SARS. We use a stochastic simulation model of the Swedish population, calibrated with survey data of travel patterns between municipalities in Sweden collected over three years. We find that a ban on journeys longer than 50 km drastically reduces the speed and the geographical spread of outbreaks. The result is found to be robust for different rates of inter-municipality transmission intensities. Travel restrictions may therefore be an effective way to mitigate the effect of a future outbreak.

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1. Introduction

Knowledge about the speed at which a contagious disease travels between geographical regions, is vital for making decisions about the most effective intervention strategies. The actual routes a disease will take are highly determined by how individuals travel in regions and between regions [1-3]. As was shown during the SARS outbreak [4], the travel patterns of today enable contagious diseases to spread to far corners of the globe at alarming rates. This exposes the need for a new type of model that incorporates travel networks. Recently, Hufnagel et al. [5] demonstrated how a simple stochastic model in conjunction with data on aviation traffic could be

used to simulate the global spread of the SARS epidemic. Using a stochastic transmission model on both a city level and globally, with each city interconnected by the international aviation network, they produced results in surprising agreement with reports of the actual case.

This study applies a modified version of the Hufnagel model to Sweden to predict the effect that travel restrictions may have on the geographical spread of an outbreak. Instead of using only the aviation network, which connects only some 30 towns in Sweden, we use survey data on *all* inter-municipal travel. Our choice of a stochastic modeling approach [6] is based on the fact that it acts out the highly random initial phase of an epidemic better than does the more commonly used deterministic approach [7,8]. The article is organized as follows: we first present the survey data used to estimate travel intensities between different municipalities in Sweden. We then introduce the simulation model to simulate the spread of the diseases and to study the effect of travel restrictions. Following this, we present the results of the simulations. We conclude our study with a discussion of the validity of the model and possible conclusions for future policy interventions.

2. Data and Methods

For this study, we use data from a random survey carried out by Statistics Sweden from 1999 through 2001. A total of 17,000 individuals took part in the survey, constituting 71.9% of the selection. 34,816 distinct inter-municipal trips were reported [9]. An inter-municipal journey is defined between two points where the individual lives, works, or conducts an errand. In other words, we treat a journey between home and work as several trips if the traveler makes stops on the way for errands, provided that a municipal border is crossed between each stop. The data was weighted to correspond to one day and to the entire population for ages 6 to 84. As it turned out, roughly 1% of the data was erroneous in a way that was not negligable and was consequently removed. From this set, we built a *travel intensity matrix*, with each element corresponding to the one-way travel intensity between two municipalities. The number of populated elements was 11,611 (to be compared with the size of the matrix, $289 \times 289 = 83,521$). Even though the matrix gives a good picture of the traveling pattern in Sweden, we must treat any intensity between two specific communities with care. This is true especially for small communities with only a single or very few journeys made between them.

A total of nine scenarios are simulated to study the effects of three levels of travel restrictions as a control measure, for three different levels of inter-community infectiousness, γ. They each start with a single infectious individual in Stockholm and treat the country as an island isolated from inflow of disease and with no possibility of traveling abroad. The traveling restrictions are divided into the following levels. In the first level, we use the complete intensity matrix. In the following two, we have removed data corresponding to journeys longer than 50 km and journeys longer than 20 km, respectively. The simulations are henceforth designated SIM, SIM50, and SIM20. In Figure 1, the data sets are displayed in geographical plots.

For γ, we use the estimate made by Hufnagel based on data from the actual outbreak, $\gamma = 0.27$. The parameter γ is influenced by the total travel intensity and the medium of travel, among others things. As we have no data for Sweden with which to calibrate our model, we need to see whether changes in γ drastically alter our conclusions. To get an idea, we compare Hufnagel's estimate of γ with twice and half of Hufnagel's original value.
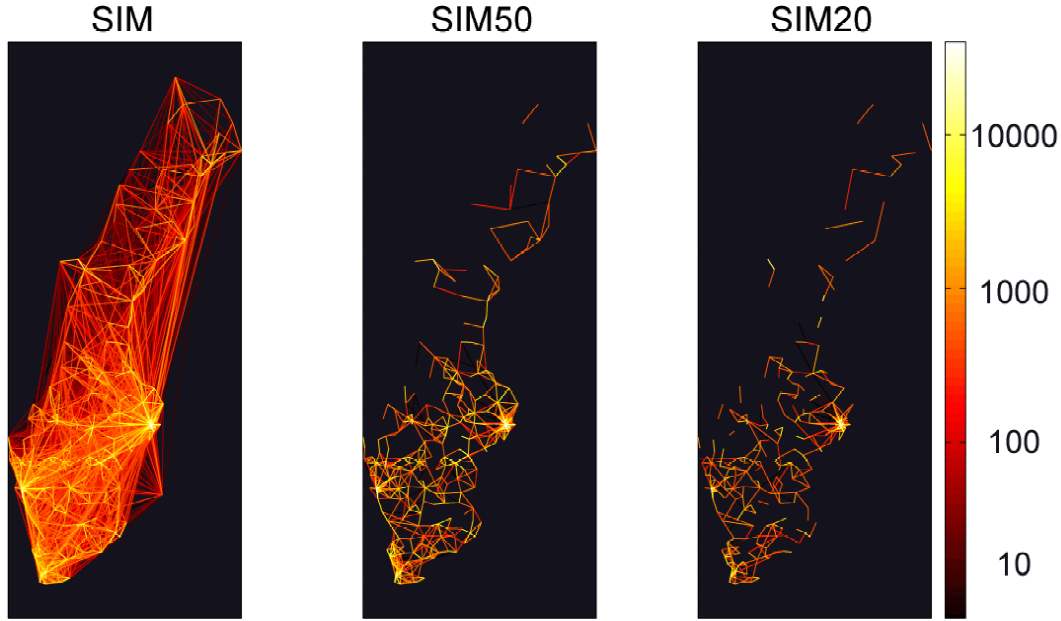

Figure 1: The inter-municipal travel network with travel intensities indicated by color lines. The scale is logarithmic in trips per day. SIM shows the complete data set. In SIM50 and SIM20, all journeys longer than 50 km and 20 km, respectively, have been removed. The lines are drawn between the population centers of each municipality, so in many cases the trips are shorter than the lines representing them.

To estimate the effect of travel restrictions, we use a simplified version of the model suggested by Hufnagel et al. [5]. The individuals in our model can be in four different states:

- **S** *Susceptible.*
- **L** *Latent, meaning infected but not infectious.*
- **I** *Infectious*
- **R** *Recovered and/or immune.*

The rate at which individuals move from one category to the next is governed by the intensity parameters α, β and v [10,11]. The transitions between different states in a municipality i can be viewed schematically as follows:

$$S_i + I_i \xrightarrow{\alpha} L_i + I_i, \quad L_i \xrightarrow{v} I_i, \quad I_i \xrightarrow{\beta} R_i. \tag{1}$$

To the first of these, we further assume a contribution from each other municipality j, resulting in the following possible transitions:

$$S_i + I_j \xrightarrow{\gamma_{j,i}} L_i + I_j .$$ (2)

As the process is assumed to be Markovian, as in Hufnagel, the time between two events, Δt, is random, taken from an exponential distribution,

$$\Delta t \in \mathrm{Exp}\left(\frac{1}{Q} \right)$$ (3)

where Q is the total intensity, the sum of all independent transmission rates:

$$Q_i^L = \alpha I_i \frac{S_i}{N_i} + \sum_{j \neq i} \gamma_{j,i} I_i \frac{S_i}{N_i} ,$$
$$Q_i^I = v L_i ,$$
$$Q_i^R = \beta I_i .$$

$$Q = \sum_i Q_i^L + \sum_i Q_i^I + \sum_i Q_i^R .$$ (5)

The simulation runs as follows: First we move forward in time with a step Δt given by Expression 3. We then randomly select the event that will occur with a probability proportional to the corresponding intensity. All intensities are then updated according to the new state, and the process is repeated until the disease dies out or the simulation period, 60 days, is passed.

3. Results

The results for all nine scenarios are plotted geographically and color-coded according to the mean incidence in Figure 2. Note the different scales beside each plot.
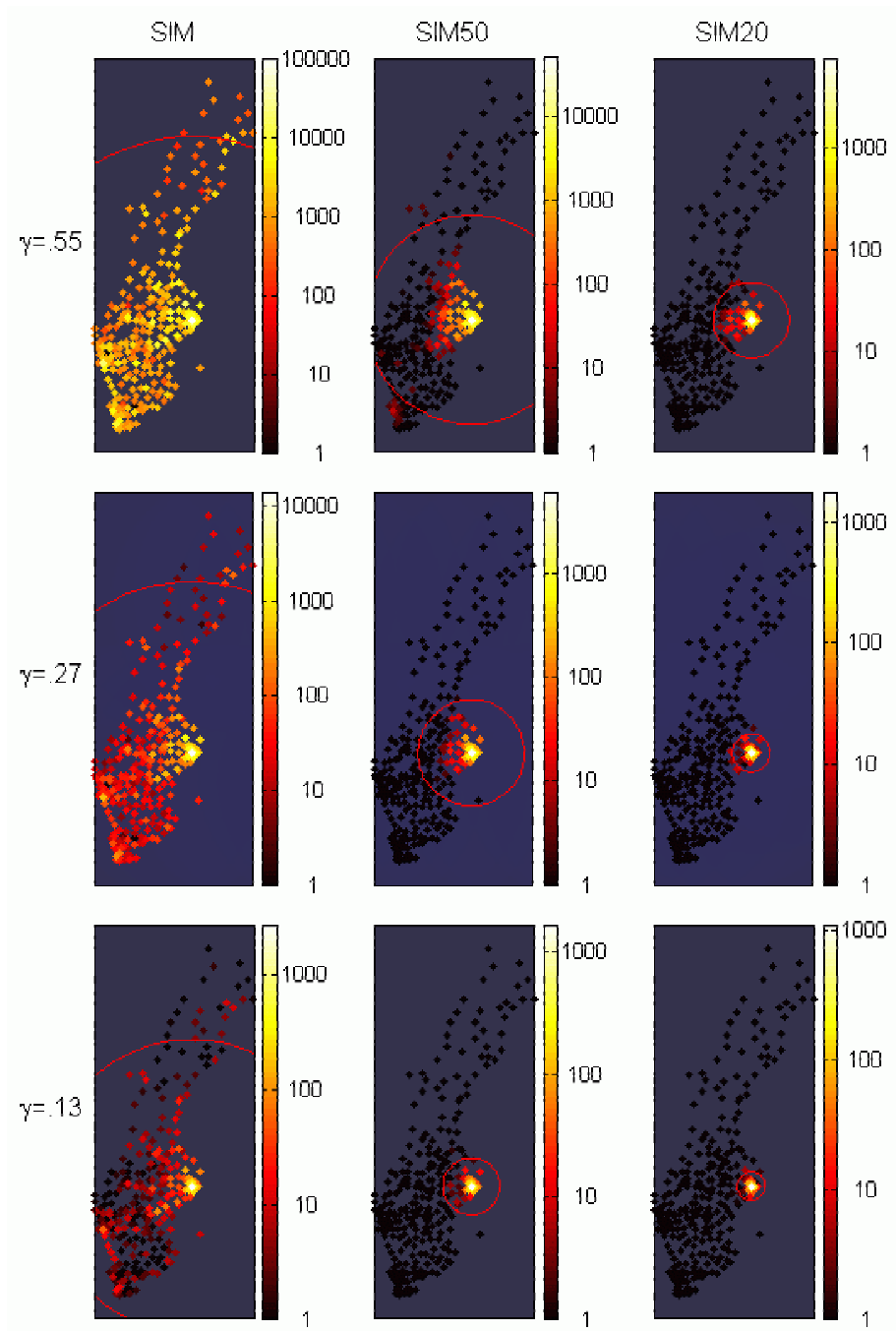
Figure 2: Geographical plot of the municipalities logarithmically color-coded according to the mean incidence. SIM depicts the complete data set. In SIM50 and SIM20, all journeys longer than 50 km and 20km, respectively, have been removed. The red circle signifies the mean extent of the epidemic from Stockholm.

A scenario with no restrictions results in an outbreak in which a majority of the municipalities become affected regardless of γ. Only the incidence differs. A ban on journeys longer than 50 kilometers stifles the dynamics of the outbreak. For the two lower values of γ, we see that the disease remains in the Stockholm area after 60 days, and for the high value of γ, the disease has not managed to spread far from the densely populated areas around the largest Swedish cities. Prohibiting journeys longer than 20 kilometers will result in an even slower spread with a small number of afflicted municipalities, mainly localized around Stockholm. What is more, the total incidence after 60 days as well as the incidence in each municipality drops as we impose the restrictions.

Table 1 compares the country's total incidence in the three simulations for which Hufnagel's estimate of γ was used. Table 2 presents the incidence broken down into a few selected municipalities.

Table 1: The table shows the main results along with miscellaneous information about the simulation. Figures refer to simulated values at the end of the run. The mean is taken over the complete set of 1000 runs. By *incidence* we mean the number of infectious, and *cumulative incidence* is the total number that was infectious at one time or another during the run.

	SIM			SIM50			SIM20		
	Result	Conf. Interval		Result	Conf. Interval		Result	Conf. Interval	
Cumulative incidence	236570	222920	250750	72770	68370	77140	18030	16860	19240
Percentage infected from another municipality	26.1	25.3	26.9	18.9	18.3	19.5	11.1	10.7	11.5
Incidence	56960	53690	60340	17350	16300	18420	4220	3947	4502
Number of afflicted municipalities	262.1	259.2	264.9	47.8	47.1	48.4	29.6	29.1	30.1
Mean incidence in municipalities	197.1	185.5	208.5	60.0	56.5	63.7	14.6	13.6	15.6
Mean time for extinction (days)	3.48	-		3.24	-		3.58	-	
Number afflicted municipalities before extinction	1.32	-		1.28	-		1.25	-	
Mean travel distance (km)	65.9	-		22.2	-		11.3	-	
Total intensity (millions/day)	4.6	-		2.9	-		1.5	-	
Number of inter-municipal one-way routes	11611	-		1493	-		830	-	
Number of extinction runs (of 1000)	262	-		297	-		303	-	

The high number of extinction runs may be surprising, but it is in accordance with the theory of Markov processes, which dictates that $1/R_0 = 37\%$ of the runs should terminate in extinction [12]. In the simulations of our study, a lower value is expected due to spread to and reintroduction from other municipalities.

The reason for the decrease in incidence is of course the limited transmission paths available to the disease. The disease, after having spread from one municipality to another will constantly be reintroduced into the originating municipality -- provided that there is a flow of travelers in the opposite direction in the travel intensity matrix. Travel restrictions limit both spread to other municipalities and

reintroduction. For comparison, had traffic been removed altogether, the incidence in Stockholm would be 917.

Table 2: A selection of municipalities[1] with the mean incidence and 90%-prediction intervals generated with bootstrapping (see table1).

Municipality	SIM			SIM50			SIM20		
	Incidence	Prediction Interval		Incidence	Prediction Interval		Incidence	Prediction Interval	
Stockholm	13 700	12 903	14 526	5 999	5 630	6 380	1 759	1 641	1 875
Gothenburg	539.2	489.4	593.6	0.1	0.0	0.3	0.0	0.0	0.0
Malmö	249.9	221.1	281.3	0.0	0.0	0.0	0.0	0.0	0.0
Huddinge	2 563	2 418	2 711	1 252	1 176	1 328	357.4	331.3	383.4
Upplands-Bro	423.4	396.7	449.8	162.0	150.6	173.6	18.0	15.3	21.2
Norrtälje	693.0	651.0	735.1	96.7	89.2	104.5	8.8	7.3	10.6
Södertälje	836.1	783.8	888.3	276.2	256.7	296.0	13.4	11.0	16.1
Västerås	637.9	592.9	684.9	21.1	16.6	26.3	0.9	0.7	1.2
Eskilstuna	511.0	474.3	548.2	34.3	28.9	40.4	6.1	5.1	7.1
Örebro	411.1	377.2	445.9	0.1	0.0	0.1	0.0	0.0	0.0
Jönköping	168.0	153.6	183.1	0.0	0.0	0.0	0.0	0.0	0.0
Linköping	390.0	356.6	425.5	1.4	1.1	1.7	0.0	0.0	0.0
Helsingborg	105.5	96.3	115.3	0.3	0.2	0.4	0.0	0.0	0.0
Borås	103.5	94.6	113.0	0.3	0.2	0.4	0.0	0.0	0.1
Gävle	412.7	384.1	442.3	16.6	10.2	25.0	0.3	0.2	0.5
Umeå	87.2	73.7	103.3	0.0	0.0	0.0	0.0	0.0	0.0
Luleå	175.2	152.3	200.4	0.0	0.0	0.0	0.0	0.0	0.0
Ljungby	21.9	20.0	24.0	0.1	0.1	0.2	0.0	0.0	0.0
Hofors	53.8	49.6	58.1	1.4	0.8	2.3	0.0	0.0	0.0
Örkelljunga	3.2	2.8	3.7	0.0	0.0	0.0	0.0	0.0	0.0

It is also clear how travel restrictions increasingly protect cities the farther they are from the capital, the focal point of the infection. The major cities of Gothenburg and Malmö are protected even though traffic into these cities is heavy. In fact, the farthest the disease ever makes it in SIM50 is Ljungby, 1471 km from Stockholm and still some 200 km from Malmö. For SIM20 the farthest city is Uddevalla, 441 km away and a suburb to Gothenburg. The mean reach of the epidemic is only 276 km and 34 km, respectively.

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[1] After Stockholm, Gothenburg and Malmö are the largest cities in Sweden. The single most traveled route is that between Stockholm and neighboring Huddinge, traveled by approximately 37,000 peopledaily, each way. The decline in incidence closely follows that in Stockholm. Upplands-Bro is representative of an outer suburb to Stockholm. Södertälje and Norrtälje are nearby towns but are not considered suburbs. Västerås and Eskilstuna are more distant, but have a fair number of commuters. The last four are small towns in southern Sweden, and the remaining ones, Örebro through Luleå, are larger towns at some distance from Stockholm with no notable commuter traffic.

4. Discussion

Our results show clearly that traveling restrictions will have a significant beneficial effect, both reducing the geographical spread and the total and local incidence. This holds true for all three levels of inter-community infectiousness simulated, γ. γ is influenced by many factors, most notably by total travel intensity, but also by the medium of travel, the behavior of the traveler, the model of dispersal by travel and by the infectiousness of the disease. Hufnagel calibrated γ using data from the actual outbreak. As mentioned, no attempt was made on our part to find the "true" value of γ in the new settings, as no such data is available for Sweden. This would be considered a flaw for a quantitative study on a SARS outbreak in Sweden. By simulating for different values of the parameter, however, we can be confident in the qualitative conclusion, namely, that the same general behavior can be expected in the unrestricted scenario and in response to the control measures, regardless of γ.

In light of the fact that inter-municipal travel heavily influences incidence even at a local level, one may justifiably be concerned about the boundary conditions. We treat Sweden as an isolated country, but quite obviously, the incidence will be underestimated for areas with frequent traffic across the borders. This includes in particular the Öresund region around Malmö, and to a lesser extent, international airports and the small towns bordering on Norway and Finland.

A total ban on all journeys longer than 50 km during an outbreak of a contagious disease that threatens public health may at a first glance look unrealistic. It may, however, be possible to ban only unnecessary journeys longer than 50 km if combined with other control measures to minimize the risk of transmission on such a journey. Such a strategy is likely to have the same effect as the scenario studied in this study. Even though there is presently no treatment or vaccine for SARS, results show that limited quarantine as suggested here drastically decreases the risk of transmission and this may well turn out to be the most expedient form of intervention. For other types of disease for which preventive treatment (pandemic flu) or vaccine (small-pox) are available, our results show that long-distance travelers are an important group for targeted control measures.

Acknowledgements

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