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# Urban exodus and the dynamics of COVID-19 pandemics

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## Abstract

In mid-march in France following the announcement of containment of persons to their home, a number of city dwellers left to the country side. Countrymen were not enthusiastic in fear of contamination and this exodus was first strongly criticised in the media. Numerical simulations presented in the present paper show that the increase in infected persons in the countryside is over compensated by the decrease of the infection in cities. At the Nation level the effects of this urban exodus were then beneficial.

Keywords: COVID-19, Urban exodus, Epidemic, Dynamics

## 1 Introduction

According to mobile phone data [5] some 1.2 millions inhabitants of the Ile de France region surrounding Paris left in prevision or after the announcement of containment by the President around march 15th 2020. Similar movements were reported in New York City[6], Lombardia and Russia. The exodus was severely criticised in the media<sup>1</sup>

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<sup>1</sup>e.g. L'Obs 3/27, Le Point 3/27, EUROPE1 radio 3/18, 20 minutes 3/17 etc.

under the argument that it would propagate the virus from cities to remote areas. In fact, in the long run, the dynamics of the epidemics depends not only upon the initial number of infected people but also upon the frequency of contacts between susceptible and infected individuals. Since contacts are less frequent in the countryside due to the lower population density less people become infected. The two effects of the exodus, initial increase of infected people from town in the countryside and decrease of contacts' frequency from these people have to be evaluated in order to conclude on the overall effect of urban exodus.

We use a simple compartmental model of populations: one compartment is the city and the other one the countryside. The simulations are based on the standard SIR (Susceptible, Infected, Recovered) model of Kermack and McKendrick [3]. To evaluate the consequences of the urban exodus we compare the numbers of deceased citizens under the influence of urban exodus to a hypothetical absence of exodus. We take into account the urban exodus by increasing (resp. decreasing) the number of initially infected citizens in the countryside (resp. in the city). And the probability of encounters is chosen higher in the city than in the countryside.

The model and the differential system are described in section (2). Simulation results are reported in section (3). Section (4) and (5) are devoted to discussions and conclusions.

## 2 The mathematical model

Let us recall the standard SIR (Susceptible, Infected, Recovered) model of [3].

$$\frac{df_s}{dt} = -\beta \cdot f_s \cdot f_i \quad (1)$$

$$\frac{df_i}{dt} = \beta \cdot f_s \cdot f_i - \gamma \cdot f_i \quad (2)$$

$$\frac{df_r}{dt} = \gamma \cdot f_i \quad (3)$$

describing the evolution of fractions of:

- $f_s$ , Susceptible, i.e healthy persons who have never been infected;
- $f_i$ , Infected persons who can infect susceptible persons on the occasion of encounters;

- $f_r$  the removed patients in a population. In fact  $f_r$  includes not only those who recovered but also the dead patients since both populations don't play any further role in the propagation of the epidemics.

$\beta$  is the infection coefficient which represents the probability of encounter of healthy and infected persons *AND* the possible following infection of the healthy person.  $\gamma$  is a probability of healing *OR* death.

The fundamental assumption of our model is the strong difference in the probabilities of encounters in the city and in the countryside.

- In the city citizens use common transportation, such as bus, metros, taxis whereas they use their car in the countryside.
- A city offers a lot of commodities such as shops and services in a small neighbourhood. The choice is more limited in the countryside since distances are larger; cost and time thus limit choices and encounters. As a consequence customer bases of different shops are disconnected and constitute communities[2] in the sense of social networks.
- Some kind of autarcy exists in the countryside; eating in restaurants among strangers is also less frequent.

Numerical evaluation of these factors to obtain contact matrices [7] used in epidemics modelling has not been done or at least is not available. But all the above described factors go in the same direction and imply a larger probability of encounters in the city. A similar approach has been taken in Li, Richmond and Roehner[4].

We then consider two populations one in the city and one in the countryside obeying the SIR equations, but with different probabilities of encounter and thus different  $\beta$  coefficients for the city and the countryside.

In order to write the coupled differential equations for the city and the countryside

- We use indices t (town) for the city and c for the country side.  $\beta$  becomes  $\beta_t$  for the city and  $\beta_c$  for the country side.  $\gamma$  related to the time evolution of the disease in infected persons is the same in cities and in the countryside.
- Since we are interested in the early stages of the epidemics when the fraction of susceptible citizen  $f_s$  is close to one, we simplify the equations by taking  $f_s = 1$  and forget about equation (1).

- Population dynamics are coupled because of commuters implied in the transfer of goods, services and persons between the city and the countryside. The coupling coefficient is called  $T$  for transfer.

The differential system is now written:

$$\frac{df_{it}}{dt} = \beta_t \cdot (f_{it} + T \cdot f_{ic}) - \gamma \cdot f_{it} \quad (4)$$

$$\frac{df_{rt}}{dt} = \gamma \cdot f_{it} \quad (5)$$

$$\frac{df_{ic}}{dt} = \beta_c \cdot (f_{ic} + T \cdot f_{it}) - \gamma \cdot f_{ic} \quad (6)$$

$$\frac{df_{rc}}{dt} = \gamma \cdot f_{ic} \quad (7)$$

where the first and second equations describe the dynamics in the city (index  $t$ ) and the third and fourth equations describe the dynamics in the countryside (index  $c$ ). The coupling terms  $T \cdot f_{ic}$  and  $T \cdot f_{it}$  correspond to the infection of locals by infected commuters.

### 3 Computer simulations

#### 3.1 Dynamics of the coupled city/countryside system

Equations (4-7) are integrated using a variable-time-step ROW4A algorithm [1].

Figure(1) e.g. was obtained with the following set of initial conditions and parameters corresponding to the early stage of the epidemics and containment conditions (low values of the  $\beta$  parameters)

$$f_{it}(0) = .01, f_{ic}(0) = .001, f_{rt}(0) = 0., f_{rc}(0) = 0., \\ \beta_t = 0.08, \beta_c = 0.04, \gamma = 0.1, T = 0.01.$$

$\beta_t$  value is an estimate of the infection coefficient after containment in France and  $\beta_c$  is a rough estimate for the countryside.  $\gamma$  corresponds to an average duration of 10 days for the disease.  $T$  is probably an overestimate, but simulation results are not much sensitive to  $T$  up to  $T = 0.1$ .  $f_{it}(0)$  and  $f_{ic}(0)$  are rough estimates of the situation in France.

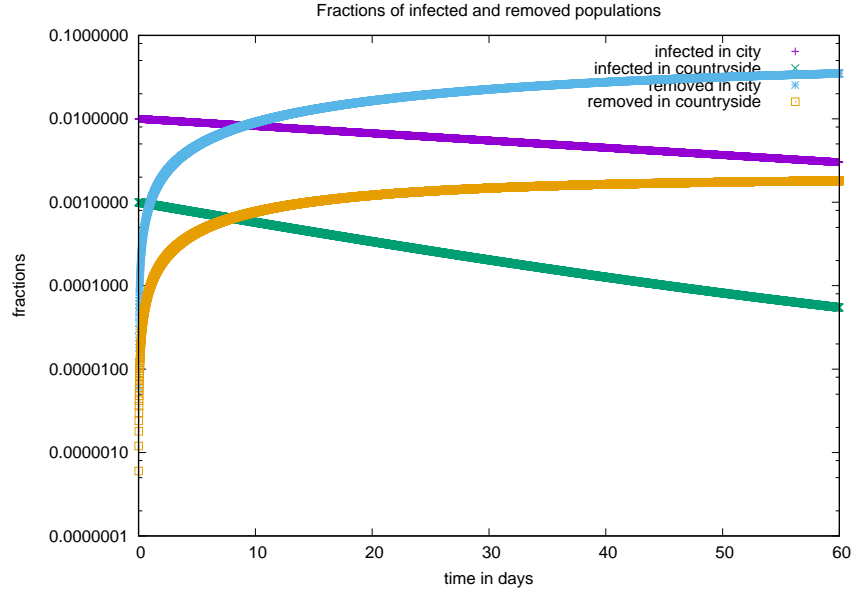


Figure 1: Evolution of the fractions of infected (the decaying exponentials) and removed patients (the increasing curves) in the city and in the countryside.

One observes on figure (1) the exponential decay of the fractions of infected people and the gradual build-up of the fraction of removed people, whether cured or dead.

### 3.2 Comparison of the dynamics in the presence or absence of urban exodus

The results of integration of two versions of system (4-7) are compared, one in the absence of urban exodus and one in the presence of urban exodus.

The two versions differ by the initial conditions and by the contagion parameters  $\beta$ . We use superscripts to refer to variables in the case urban exodus (exo) and its absence (noexo).

In the absence of urban exodus one fixes the initial values of the infected populations in the city ( $f_{it}^{noexo}(0) = 0.01$ ) and in the countryside ( $f_{ic}^{noexo}(0) = 0.001$ ). In the case of an urban exodus the initial values of the infected populations in the city are decreased to e.g ( $f_{it}^{exo}(0) = 0.009$ ) and increased in the countryside to e.g.

$(f_{ic}^{exo}(0) = 0.0011)^2$ . In both versions initial densities of the fractions of removed individual are null.

All parameters in the equations are the same except for the contagion parameters values. We used  $\beta$  values corresponding to the containment phase of the epidemics. In the case of exodus we decrease the  $\beta$  coefficient in town and increase it accordingly in the countryside e.g. in the absence of exodus,  $\beta_t^{noexo} = 0.09$  and  $\beta_c^{noexo} = 0.04$ , in the case of exodus,  $\beta_t^{exo} = 0.085$  and  $\beta_c^{exo} = 0.045$ .

We evaluate the outcome of the epidemics by monitoring  $f_r(t)$  the fractions of cured and dead patients at the end of the containment, after 60 days. It also roughly reflects the total fraction of dead patients which is smaller by a factor of order 1/100, (smaller than 5 perc.) in France.

The national impact of the epidemics at the national level is proportional to the sum of these fractions in the city and the countryside.

The impact  $I$  of the urban exodus is the difference in national impacts in the presence or absence of urban exodus.

$$I = [f_{rt}^{exo}(60) + f_{rc}^{exo}(60)] - [f_{rt}^{noexo}(60) + f_{rc}^{noexo}(60)] \quad (8)$$

A typical set of parameters and initial conditions is then:  $\gamma = 0.1$ , death or cure in some 10 days.

$T = 0.01$ , 1 perc. commuters involved in transportation between the city and the countryside.

In the absence of exodus  $\beta_t^{noexo} = 0.09$  and  $\beta_c^{noexo} = 0.04$ , in the case of exodus,  $\beta_t^{exo} = 0.085$  and  $\beta_c^{exo} = 0.045$ .

Initial fractions of cured and dead patients initially 0.

$df_{it}(0) = 0.01$  and  $df_{ic}(0) = 0.001$  in the absence of urban exodus,  $df_{it}(0) = 0.009$  and  $df_{ic}(0) = 0.0011$  in the case of an urban exodus

We tested a large set of initial conditions and parameters. Figure 2 e.g displays the decrease of the impact of the exodus when the conditions in the country side are chosen closer to those in the city. One observes the influence on the decrease of the benefit of exodus (1) due to the increase of the initial fraction of infected people in the countryside  $f_{rc}^{exo}(0)$  and (2) due the increase the infection rate in the countryside  $\beta_t^{exo}$ .

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<sup>2</sup>The increase in population density in the countryside is smaller than the decrease in the city since it is diluted into several regions.

$\beta_c^{noexo}$	$\beta_c^{exo}$	$\beta_t^{noexo}$	$\beta_t^{exo}$	$df_{rc}^{noexo}$	$df_{rt}^{noexo}$	$df_{rc}^{exo}$	$df_{rt}^{exo}$	$-I$
0.04	0.045	0.09	0.085	0.00185	0.0451	0.00372	0.0357	0.009223

Table 1: Simulation results for one set of  $\beta$  parameters on each line. Columns 1-4 give the infection parameters  $\beta$ , columns 5-8 the fractions of removed patients after 60 days of containment, and the last column the total decrease in the fraction of removed patients thanks to urban exodus.

For a large domain of initial conditions and parameters which most probably include real conditions in France, the balance between the fraction of removed people in the case of urban exodus relative to its absence is always beneficial: less people are affected by the epidemics at the national level.

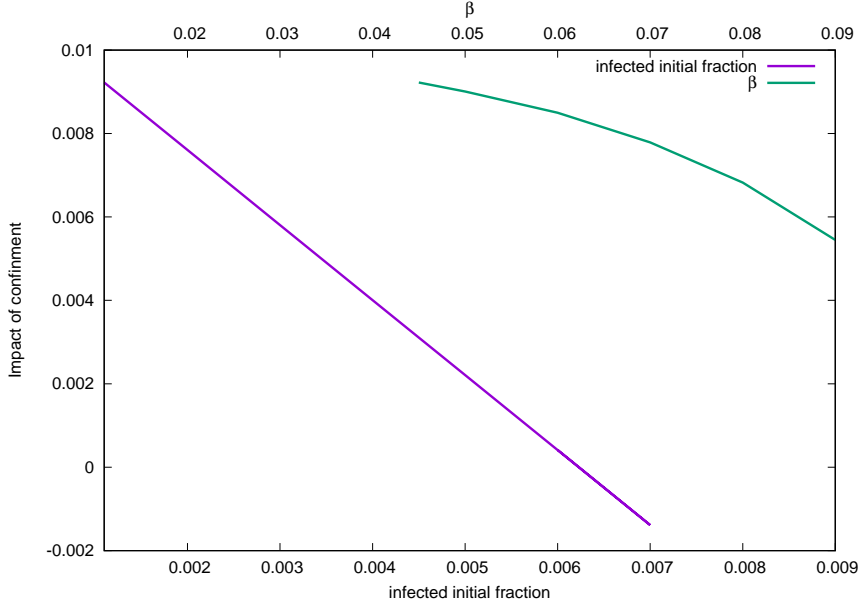


Figure 2: Impacts of containment as a function of the initial fraction of infected patient in the countryside (violet curve, lower scale) and as a function of the infection rate in the countryside  $\beta_t^{exo}$  (green curve, upper scale). All other parameters are given above.

The sufficient conditions for such a beneficial outcome are :

- $\beta_t^{exo} < \beta_t^{noexo}$ , encounters less frequent in the city when exodus



- $\beta_c^{exo} > \beta_c^{noexo}$ , encounters more frequent in the countryside when exodus
- $f_{it}(0)^{exo} < f_{it}^{noexo}$ , initial density of infected people lower in the city when exodus
- $f_{it}(0)^{exo} > f_{it}^{noexo}$ , initial density of infected people higher in the countryside when exodus

A simple argument explains these results. Let us start from one infected individual. The first infected individual infects on average  $\beta$  individuals which themselves infect on average  $\beta^2$  individuals and so on. At each step  $n$ ,  $\beta^n$  more individuals are infected. Summing this geometric series of ratio  $\beta$  to infinity gives the size of cascade of infections  $SIC$ :

$$SIC = \frac{1}{1 - \beta} \quad (9)$$

which corresponds exactly to the figures obtained when integrating system (4-7) for large times (1000 days) with a zero transfer coefficient  $t$ .

The smaller values of  $\beta$  in the countryside directly explain the beneficial aspects of the urban exodus.

## 4 Discussion

The SIR equations are a crude model of the dynamics of an epidemics but we considered it adequate in view of our limited aims, namely to figure out whether the impact of the urban exodus would be positive. We further approximated by condensing the urban areas into one compartment and did the same for the countryside areas.

One fundamental assumption is that urban dwellers were only a small fraction of the country men in the areas they moved to. According to INSEE statistics[5], the percentages of population increase due to the urban exodus were 7 perc in Orne, 6 perc. in Lot, Haute Loire, Gers and Ardèche, and lower in other départements. Possible exceptions could have been small islands or coastal regions. In general, we miss such information since data are collected at the level of departments. In one case the Agence Régionale de Santé of Bretagne mentions a 30 perc. increase of COVID deaths in Morbihan.

One other fundamental assumption is that a non-zero virus infection

- Occurred in the countryside before urban exodus;
- and carried on because of regular travellers.

Urban exiles were certainly not the unique spark which ignited the fire.

We have chosen the infection parameters under the implicit assumption that city dwellers would observe the same containment rules in the countryside as in the city.

COVID refugees were blamed especially because they were wealthier persons possessing country homes while physical workers could not afford to leave their job. It is true that most of them could work online or were enjoying comfortable pensions. On the other hand, those who remain in the city indirectly benefited from the local decrease in density population and the resulting decrease of the contagion coefficient. In the case of the set of parameters reported in table 1, the decrease in  $f_{rt}$  is 0.0095, corresponding to 20 perc. of casualties. Even if this figure is probably an overestimation since the two populations don't fully mix, the effect is still beneficial also for those who didn't leave.

One of the issues raised by officials and journals was the carrying capacity of the countryside either in terms of medical facilities or even food supply. In practice it turned out that shortages in Intensive Care Units occurred mostly in large cities such as Mulhouse, Strasbourg and Paris and not at the level of smaller town hospitals. There were sometimes initial rushes to buy supplies in supermarkets but there were no shortages anywhere.

## 5 Conclusions

In contradiction with popular and media wisdom our simulation demonstrate that urban exodus had an overall beneficial effect on the covid epidemics. Of the two contradictory effects, increase of local cases due to the arrival of city dwellers in the countryside and decrease of the epidemics in the city due to the diminution of contagion, the second effect is the most important in numbers.

One can understand that “human nature” is such that one cares more about one's hazards than about other's benefits, and the same applies to one's family rather than strangers. This explains some reactions in the countryside.

The castigation of moving city dwellers by the french media raises more questions. In general people have a poor understanding of ex-

ponential dynamics. Often exponential is interpreted as fast without taking into account the magnitude and the sign of the exponent. And too often journalists care more about negative moral opinions than scientific reasoning.

It is worth noticing that the same reactions to epidemics that Occurred in the Middle Ages such as strangers exclusion can still be observed nowadays.

### Acknowledgements

The present work was done while in containment outside Paris. The idea germinated when the pharmacist I visited told me to go back to Paris while his colleague menaced to call the police. I thank Claude Weisbuch and Sophie Bienenstock for their help in writing the manuscript.

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