Transportation, Pathogens, Culture: Dynamic Graph Model of 2019-nCoV Transmission

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Abstract

Since the outbreak of the novel coronavirus epidemic in Wuhan City, the rapidly escalating situation has resulted in over 300 fatalities and more than 10,000 infections. Over one hundred cases have been reported outside China, impacting more than a dozen countries globally. Researchers have published the complete genome sequence of the coronavirus and are expediting the development of rapid diagnostic kits, effective therapeutics, and prophylactic vaccines. The initially rapid growth in confirmed cases precipitated lockdown measures in Wuhan and surrounding cities. Scientists worldwide have endeavored to construct mathematical models to forecast infection case numbers in the forthcoming days. However, primary factors such as transportation networks and cultural practices have not been adequately considered. Our model does not aim to precisely predict infection case counts, but rather to simulate the dynamic evolution of public health emergencies and the respective contributions of various influencing factors. We anticipate that our model and simulations will furnish global public health institutions with enhanced insights and perspectives, thereby facilitating the design of superior prevention and control strategies.

Full Text

Transportation, Pathogenic Microorganisms, and Culture: A Dynamic Graph Model of 2019-nCoV Transmission

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Since the outbreak of the novel coronavirus in Wuhan, the rapidly escalating situation has resulted in over 300 deaths and more than 10,000 infections. Over one hundred cases have been confirmed outside China, affecting more than a dozen countries worldwide. Researchers have reported the complete genome sequence of the coronavirus and are rapidly developing rapid diagnostic kits, effective treatments, and preventive vaccines. The initial surge in confirmed cases triggered lockdowns in Wuhan and nearby cities. Scientists worldwide have attempted to establish mathematical models to predict infection numbers in the coming days. However, major factors such as transportation and cultural practices have not been adequately weighted. Our model does not aim to precisely predict the number of infection cases but rather to simulate the dynamics during public health emergencies and the contributions of different influencing factors. We hope our model and simulations can provide global public health agencies with additional insights and perspectives to design better prevention and control strategies.

In the model shown in Figure 1 [Figure 1: see original paper]A, we designed a dynamic graph model centered on a transportation module, as people constantly migrate between locations via various means of transport, and close contact during migration is considered a critical venue for human-to-human transmission. Within the transportation module, we established models for taxis, buses, subways, and walking with different capacities. We then placed fixed residential areas, public places, and hospitals around the transportation module. Finally, we attached isolation sites to hospitals. In each simulation round, every healthy individual starts from a residential area, traverses the graph structure, and returns to the residential area. After the incubation period, infected individuals proceed to hospitals and remain there or in isolation sites if space permits. Otherwise, they return to residential areas and attempt to seek medical care the following day. Healthy individuals become infected when they encounter infected individuals during transportation or in any stationary area. At the beginning of each simulation, we place one infected individual in the model and observe transmission under various conditions.

Although individuals with severe symptoms are the primary drivers of pandemic spread, data from Chinese cases in this outbreak show signs of asymptomatic transmission. Therefore, we first investigated the impact of asymptomatic transmission. We assumed that asymptomatic transmission capacity increases linearly during the incubation period and reaches maximum intensity when symptoms appear. We designated the incubation period length as 7 days and compared it with a symptomatic transmission model. Strikingly, asymptomatic transmission infected 50% of the population in only half the time required for symptomatic transmission (Figure 1B). This may be because symptomatic individuals are more easily identified and removed from the public, while asymptomatic spreaders inadvertently transmit the virus, facilitating faster spread. We also simulated scenarios with different lengths of infectious asymptomatic periods and observed that longer infectious incubation periods significantly accelerated transmission, likely because infectious individuals who feel well remain active outside for longer periods, causing more infections (Figure 1C).

Figure 1. Dynamic graph model and simulation results. In simulations, infec-

tion probability was set at 20%, with virus transmission probability as a linear function of infection events. A. Dynamic graph model for infectious disease outbreak; B. Whether transmission patterns allow asymptomatic transmission; C. Impact of various lengths of infectious asymptomatic periods on virus spread; D. Relationship between number of imported cases and outbreak speed; E. Impact of different transportation modes on virus transmission speed; In the US-like city simulation, public transportation modules were removed from the model; in the underdeveloped city simulation, public transportation and public area modules were removed, and hospital bed capacity was reduced by 50%; F. Social activities accelerate virus transmission speed; G. Wearing masks and thorough handwashing can greatly reduce the number of infected cases; In simulations, personal protection reduced infection and transmission probabilities by 90%; H. City lockdown greatly prevents transmission.

Since the coronavirus outbreak, many cities have confirmed cases, most originating from Wuhan. We evaluated the relationship between the number of imported cases and virus infection of the urban population. As shown in Figure 1D, more imported cases in the initial stage lead to earlier attainment of 50% population infection.

Since transportation appears to be a major factor affecting transmission speed, we simulated typical cities worldwide using different preferred transportation modes. For example, in China, public transportation such as buses, subways, and trains is the daily commuting method, while cars are the most common commuting method in the United States. We also included a hypothetical impoverished city with very limited public transportation. We found that Chinese cities with advanced public transportation are particularly vulnerable to virus spread, while limited public transportation in a hypothetical poor/underdeveloped city prevents virus transmission (Figure 1E). Since most American families travel by car, inter-household virus transmission is slowed. This suggests that modern cities with convenient public transportation not only provide a pleasant lifestyle but also facilitate rapid epidemic spread.

Next, we evaluated how culture and social activities affect disease transmission. The coronavirus outbreak spanned the Lunar New Year, during which most Chinese people return to their hometowns from their workplace cities. For example, before the lockdown, over 5 million people left Wuhan for the New Year holiday. Most infected individuals went to small cities in the same province, but a substantial portion went to other Chinese cities, and a small number went abroad. After the first day of the Lunar New Year, visiting relatives is a Chinese tradition that may last for a week. We simulated family gatherings during the Spring Festival and observed how this tradition would promote virus transmission. As shown in Figure 1F, earlier gatherings during the outbreak promote widespread transmission. Fortunately, administrative agencies at all levels widely publicized the serious consequences of social gatherings during the 2019-nCoV outbreak, so the Chinese public stayed home and avoided contact with others during the Spring Festival.

During outbreaks, cities are typically locked down and people are required to wear masks in public places and wash hands frequently to prevent virus spread. We found that both personal protection (Figure 1G) and city lockdowns (Figure 1H) immediately stopped virus transmission, and earlier implementation of these measures reduced the maximum number of infected cases. Although city lockdown seems a radical administrative action with significant economic impact, the decisive action taken by Chinese authorities attempted to prevent global spread of the virus.

In summary, we conclude that the decisive actions taken by Chinese authorities—implementing city lockdowns and requiring personal protection—effectively reduce virus transmission. Finally, effective communication and a well-educated public are key to containing pandemic spread. We call on all countries' CDCs to pay special attention to possible asymptomatic transmission, which would cause major changes to isolation procedures in various countries.

Project code: https://github.com/xjtu-omics/2019-nCoV_graph_model

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Note: Figure translations are in progress. See original paper for figures.