Public Health 200 (2021) 15–21

Contents lists available at ScienceDirect

Public Health

journal homepage: www.elsevier.com/locate/puhe

Original Research

Investigating the relationship between reopening the economy and implementing control measures during the COVID-19 pandemic

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ARTICLE INFO

Article history:
Received 18 April 2021
Received in revised form
27 July 2021
Accepted 1 September 2021
Available online 11 September 2021

Keywords:
COVID-19
Face mask
Social distancing
Transmission dynamics
Second outbreak

ABSTRACT

Objectives: The COVID-19 pandemic has resulted in an enormous burden on population health and the economy around the world. Although most cities in the United States have reopened their economies from previous lockdowns, it was not clear how the magnitude of different control measures—such as face mask use and social distancing—may affect the timing of reopening the economy for a local region. This study aimed to investigate the relationship between reopening dates and control measures and identify the conditions under which a city can be reopened safely.
Study design: This was a mathematical modeling study.
Methods: We developed a dynamic compartment model to capture the transmission dynamics of COVID-19 in New York City. We estimated model parameters from local COVID-19 data. We conducted three sets of policy simulations to investigate how different reopening dates and magnitudes of control measures would affect the COVID-19 epidemic.
Results: The model estimated that maintaining social contact at 80% of the prepandemic level and a 50% face mask usage would prevent a major surge of COVID-19 after reopening. If social distancing were completely relaxed after reopening, face mask usage would need to be maintained at nearly 80% to prevent a major surge.
Conclusions: Adherence to social distancing and increased face mask usage are keys to prevent a major surge after a city reopens its economy. The findings from our study can help policymakers identify the conditions under which a city can be reopened safely.

Introduction

The COVID-19 pandemic has resulted in tremendous health and economic losses in the United States and globally.[1] Despite tremendous risks, most US states and cities have reopened their economies from previous lockdowns. The latest research has documented the effectiveness of public health control measures—such as face mask use and social distancing—in curbing the spread and mitigating the severity of the COVID-19 pandemic.[2–8] When city or state officials make the important decision of reopening the economy, they have to emphasize the importance of

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https://doi.org/10.1016/j.puhe.2021.09.005
0033-3506/

face mask use and social distancing as a way to prevent a future surge of COVID-19 infections.[4,7] In addition to enacting and ensuring public health control measures, the timing of reopening also plays an important role in preventing a future surge. Reopening a city or state too soon may not control the epidemic effectively even if control measures are in place.[9] On the other hand, a delay in reopening will result in a more severe economic toll, which will, in turn, affect both the mental and physical health of the residents.[10] Local government officials need more evidence to make wise reopening decisions that would slow the spread of the virus while sustaining the economy.

In this study, we use a dynamic model of the COVID-19 epidemic to investigate the relationship between reopening dates and control measures (i.e. face mask and social distancing) and identify the conditions under which a city can be reopened safely. We use New York City (NYC) as a case study because NYC was the epicenter of the pandemic in the United States and has rich COVID-19-related data that can be used to develop and validate the model.

Mathematical models of COVID-19 have been widely used to inform policies and interventions to curb the pandemic.[11] Unlike most existing models,[12–14] our model captures both symptomatic and asymptomatic transmissions and simulates transmission in both public settings and households. [6,16,17,23,25–27] Our model provides a relatively realistic representation of disease progression specific to COVID-19 in NYC. We predict the risk of a major COVID-19 surge after reopening under different levels of control measures and the resultant new COVID-19 infections and deaths. The findings from this study will provide important evidence for the government officials in NYC and other states and cities to make more informed, targeted decisions on strategies for reopening the economy and controlling the pandemic.

Methods

Data sources

We obtained NYC COVID-19 data, including the number of daily and total confirmed cases and deaths, from the NYC Department of Health and Mental Hygiene.[15] We used data from February 29 to June 7, 2020, because NYC reopened its economy on June 8, 2020, and only data before the reopening date would allow us to capture the COVID-19 epidemic under city lockdown (see Table S1 in the Supplementary Document for data details). These data were also used to estimate and calibrate the unknown parameters of the mathematical model. Other disease progression parameters and behavior data related to COVID-19 were estimated based on the published literature (see Table S2 in the Supplementary Document for details about parameter estimation).

Model structure and assumptions

We developed a dynamic compartment model to capture the transmission dynamics of COVID-19 in NYC. The model has been validated extensively in our previous studies and used to study pandemic control strategies such as face mask use and vaccination.[16,17] Fig. 1 shows the structure of the compartment model. In the model, we considered two different infection routes: one was transmission through public contacts, and the other was transmission through household contacts. Susceptible individuals became infected by contacts with latent, asymptomatic, and undiagnosed infections with mild and severe/critical symptoms (a detailed model description is provided in the Supplementary Document).

Our model considered three main prevention and control measures, including social distancing, handwashing, and face mask use. On March 20, 2020, New York State Governor Andrew Cuomo announced the “New York on PAUSE” Executive Order, so we assumed that starting from March 20, the public contact rate would decrease gradually, described by a decreasing logistic function. However, the contact rate in households would gradually increase, described by an increasing logistic function. Note that contact rate refers to the number of social contacts that may lead to virus transmission (details about the logistic functions for capturing contact rates are provided in the Supplementary Document). We also assumed that the proportion of frequent handwashing among people in NYC would increase from 77% to 95%.[18] Based on a literature review, we estimated that the effectiveness of handwashing in preventing COVID-19 infection is 42% (13–62%), which means frequent handwashing would reduce the risk of COVID-19 infection by 42% among susceptible individuals.[19]

The US Centers for Disease Control and Prevention (CDC) started recommending face mask use by the general public on April 3, and after 2 weeks, on April 17, an Executive Order was implemented that required all residents over age 2 years in the State of New York to wear masks or face coverings when they are in public and social distancing is impossible. Based on a systematic review and meta-analysis of the effectiveness of face mask use for preventing COVID-19,[20] we estimated that the effectiveness of face mask use in preventing COVID-19 transmission was 85%, which means individuals wearing a face mask would have an 85% less risk of contracting COVID-19 compared with those without a face mask. Table S2 in the Supplementary Document presents the values of all model parameters and their sources.

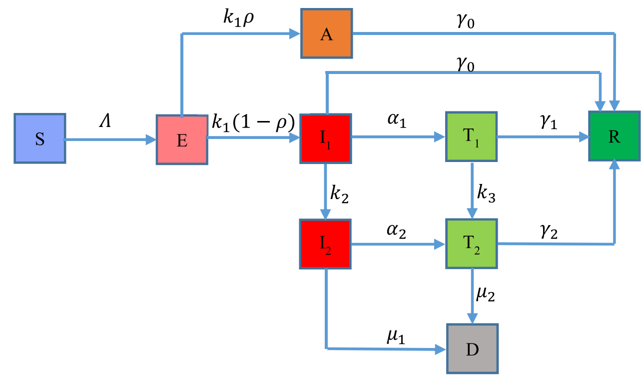

Fig. 1. Flowchart of COVID-19 transmission model in New York City. The total population is divided into nine compartments: susceptible individuals (S), latent individuals (E), asymptomatic infections (A), undiagnosed infections with mild/moderate (I_1) and severe/critical symptoms (I_2), diagnosed infections with mild/moderate (T_1) and severe/critical symptoms (T_2), recovered (R), and deceased (D) cases. The force of infection is denoted as Λ, which involves two transmission patterns: public settings (e.g. public transportation, supermarkets, offices, etc.) and households. The model includes three control measures: handwashing, social distancing, and face mask use. The average incubation period is $1/k_1$, and the probability that an individual is asymptomatic is ρ. Infectious individuals with mild/moderate and severe/critical symptoms are diagnosed and treated at the rates α_1 and α_2, respectively. We assume these diagnosed individuals are isolated strictly and could not further infect others. Undiagnosed and diagnosed mild/moderate cases progress to the severe/critical stage at the rates k_2 and k_3, respectively. Asymptomatic infections and undiagnosed mild/moderate cases are assumed to recover naturally at the rate γ_0. Diagnosed mild/moderate and severe/critical cases will recover at the rates γ_1 and γ_2, respectively. Undiagnosed and diagnosed severe/critical cases will die because of the disease at the rates μ_1 and μ_2, respectively.

Model calibration

We calibrated and validated our model based on the NYC COVID-19 data. More specifically, we estimated the unknown parameters and initial values in the model by using a non-linear least square method.[21] Based on these estimates, we further estimated the mean values and 95% confidence intervals (CIs) for unknown parameters and initial values by using a Markov Chain Monte Carlo approach.[21] We used the Metropolis–Hastings (M-H) sampling algorithm to calculate 10,000 times and used the last 1000 iterations to derive the mean values and 95% CI of unknown parameters (see Table S2 in the Supplementary Document). All simulation runs, and analyses were performed on the MATLAB R2020a platform. We validated the model by comparing model estimated values with the daily reported data (see Fig. S3 in the Supplementary Document for details about model validation).

Simulated policy scenarios

We conducted three sets of policy simulations to investigate how different reopening dates and magnitudes of control measures would affect the COVID-19 epidemic. First, we varied the reopening date and assessed the risk of a major surge of COVID-19 under each scenario. We examined four alternative reopening dates, including June 8, July 8, August 8, and September 8, 2020. For each reopening date, we fixed the contact rate in public settings and varied the face mask usage from 55%, 65%, to 85%. We also fixed the face mask usage and varied the public contact rate from 70%, 85%, to 100%. The results from these simulated policy scenarios are shown in Figs. 2 and 3.

Second, we fixed the reopening date on June 8, which is the actual reopening date, and then varied the face mask usage and public contact rate simultaneously. We assessed what combinations of face mask usage and public contact rate would lead to a major surge in the future. If there were a major surge, we assessed if it was less or more severe than the first wave of the epidemic. Fig. 4 presents the results from this set of policy scenarios.

Third, we assessed the effect of different face mask usage on the total number of infections and asymptomatic infections. As the prevalence of face mask use has been changing dramatically in the United States over the course of the pandemic and there is a large geographical variation, we conducted simulation analyses under three scenarios, including (1) the worst-case scenario (0% face mask use), (2) the status quo scenario (85% face mask use), and (3) the best-case scenario (100% face mask use). Fig. 5 presents the results from this set of policy scenarios.

Sensitivity and uncertainty analysis

We performed sensitivity analyses to explore how the magnitudes of control measures could affect the epidemic under different reopening dates. Specifically, for different reopening dates, we examined the changes in the number of infections and deaths by varying face mask usage and contact rate (the results are presented in Fig. S6 in the Supplementary Document). Finally, we examined how the uncertainty in the effectiveness of face masks could affect the epidemic (the results are shown in Fig. S7 in the Supplementary Document).

Results

Projected epidemic trend

Our model projected that with the current level of control measures, the cumulative number of COVID-19 cases would reach

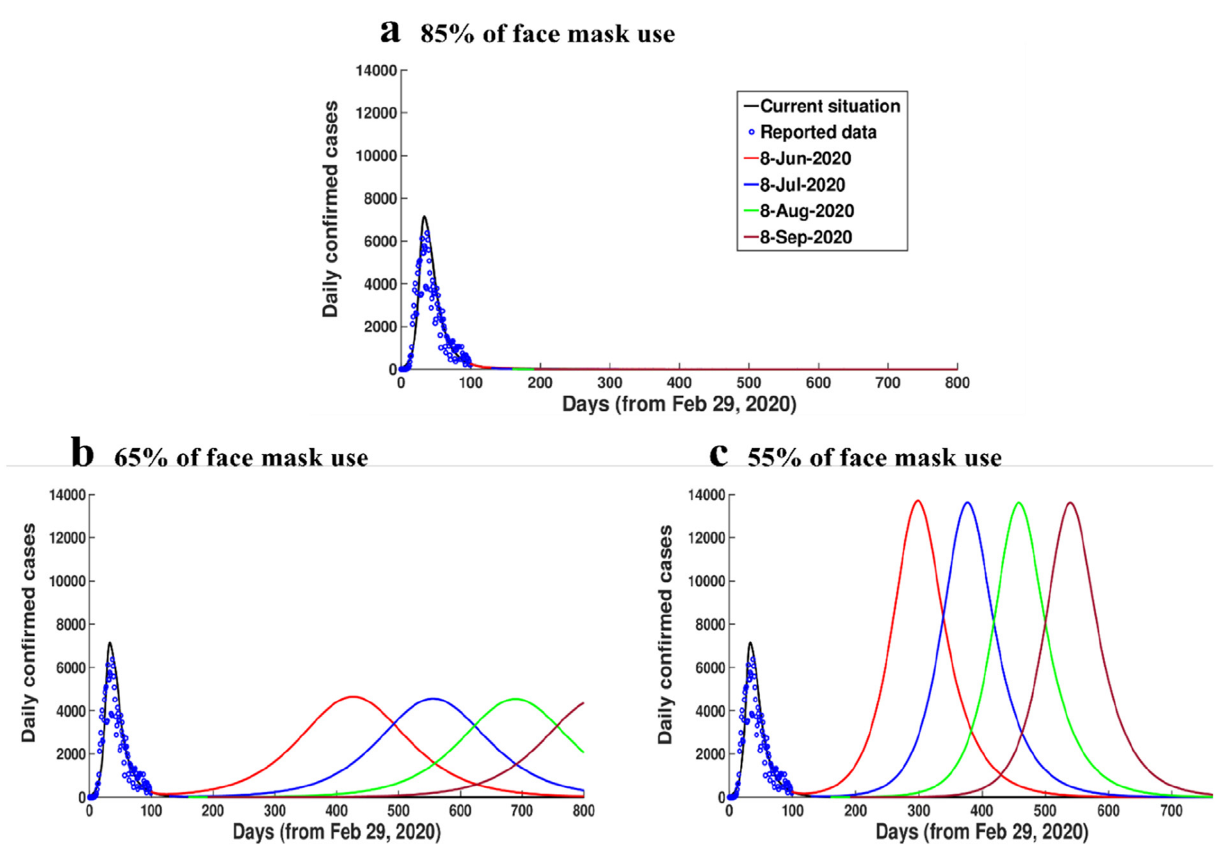

Fig. 2. Impact of different face mask usage on the trend of COVID-19 in NYC with different reopening dates. (a, b, and c) The face mask usage are 85%, 65%, and 55%, respectively. The red, blue, green, and purple curves represent the scenarios in which the reopening started from June 8, July 8, August 8, and September 8, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

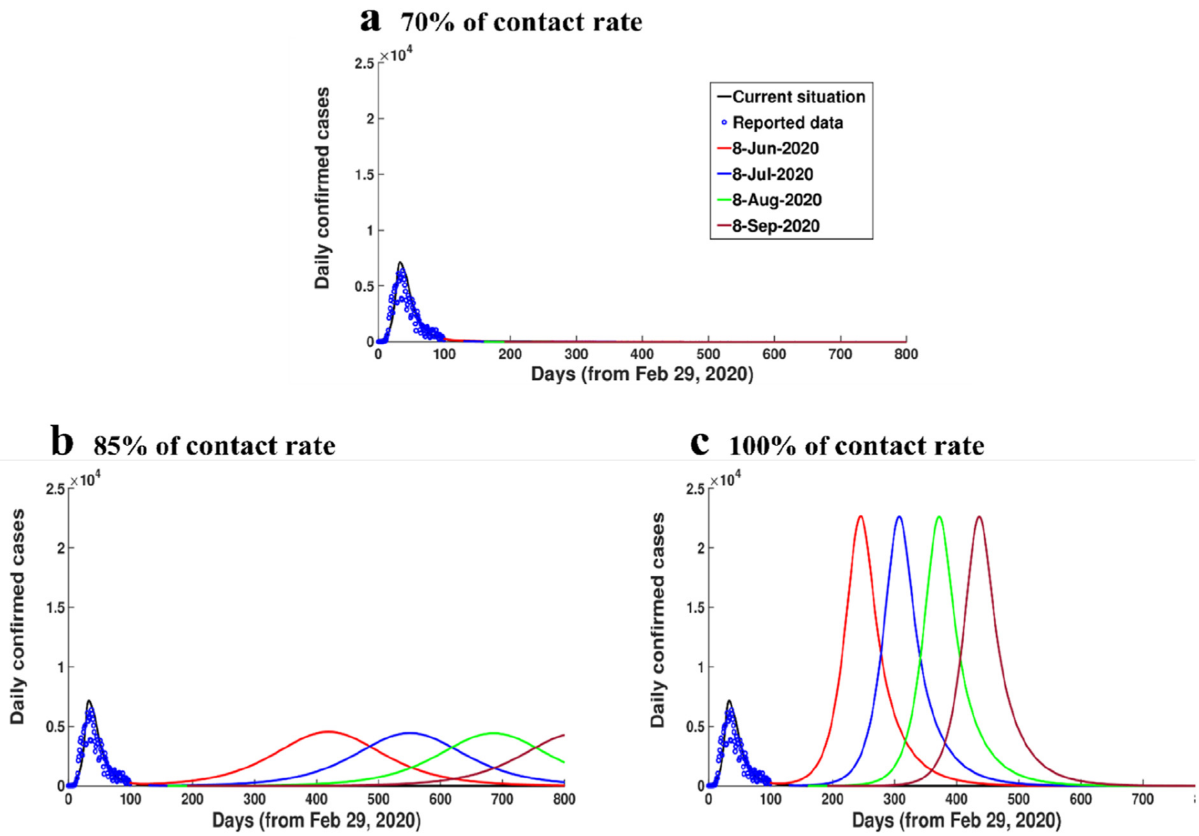

Fig. 3. Impact of different contact rates on the trend of COVID-19 in NYC with different reopening dates. (a, b, and c) The contact rates in public settings were 70%, 85%, and 100%, respectively. The red, blue, green, and purple curves represent the scenarios in which the reopening started from June 8, July 8, August 8, and September 8, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

561,647 (525,961–597,332) at the end of the epidemic in NYC. Among them, 283,576 (265,558–301,593, 50.49%) would be minimally symptomatic or asymptomatic infections (Fig. 5). Among the remaining 278,071 (260,403–295,739, 49.51%) infections that exhibited symptoms, 210,780 (197,380–224,180) would be symptomatic, and 65,023 (60,868–69,178) would be hospitalized (see Fig. S3 in the Supplementary Document).

Our model estimated that 63.93% (59.96%–67.90%) of infections were because of transmission from infected individuals with minimal or no symptoms. In particular, the percentage due to transmission from presymptomatic individuals in their incubation period was 34.71% (32.56%–36.87%), whereas the percentage due to transmission from asymptomatic individuals was 29.22% (27.40%–31.03%). We also found that 348,793 (326,699–370,886, 62.14%) cases were infected through public contact, whereas 212,854 (199,255–226,452, 37.86%) cases were infected through family contact (Fig. S4 in the Supplementary Document).

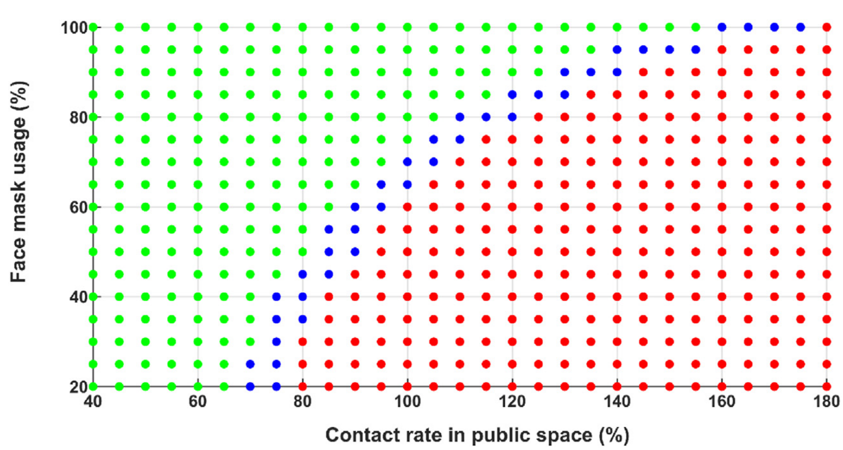

Fig. 4. Impact of various combinations of face mask usage and public contact rate on the COVID-19 epidemic after reopening on June 8 (green dots: there will be no second wave of COVID-19; blue dots: there will be a minor second wave that is less severe than the first wave; red dots: there will be a major second wave that is more severe than the first wave). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

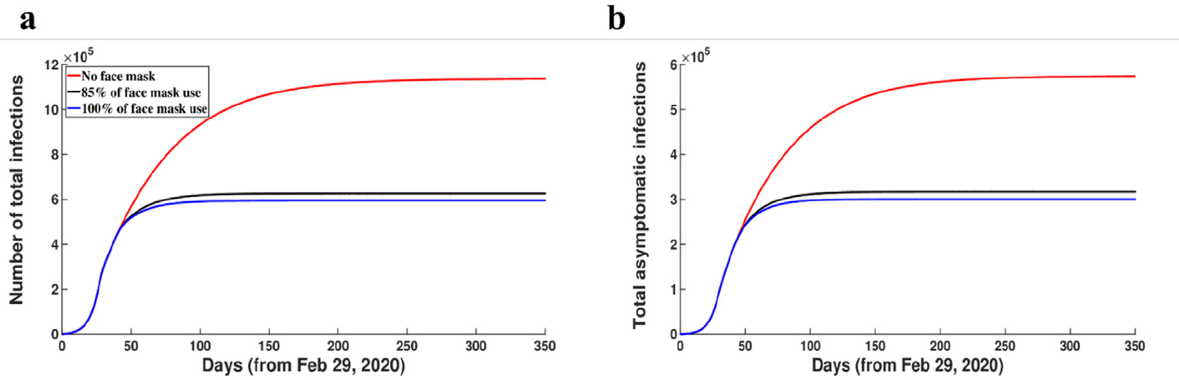

Fig. 5. Impact of different face mask uses on the number of new infections (a) and asymptomatic infections (b). (Red curve: 0% face mask usage; black curve: 85% face mask usage; blue curve: 100% face mask usage). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

Projected impacts of different reopening dates

Figs. 2 and 3 showed the impacts of various face mask usage and public contact rates on the pandemic if reopening were implemented on different dates. After reopening, if the contact rate increased to the prepandemic level and the face mask usage was maintained at 85%, a major surge of the epidemic would be prevented (Fig. 2a). However, if face mask usage was reduced to 65%, then a moderate epidemic would occur (Fig. 2b). In this case, the final cumulative deaths would be fivefold greater than the current situation (Fig. S5b in the Supplementary Document). A 55% face mask usage would result in a major surge about twice greater than the current outbreak (Fig. 2c), and the final cumulative deaths would be eight times greater than the current situation (Fig. S5c in the Supplementary Document). Postponing the reopening date would delay a major surge but not alter its potential magnitude if the other control measures stay constant.

In contrast, after reopening, if face mask usage were reduced to 45%, a major surge of the epidemic could be prevented if the contact rate was less than 70% of the prepandemic level (Fig. 3a). However, if the contact rate increased to 85% of the prepandemic level, then a moderate epidemic would occur (Fig. 3b). In this case, the final cumulative deaths would be five times greater than the current situation (Fig. S5e in the Supplementary Document). A 100% contact rate would result in a major surge about three times greater than the first wave (Fig. 3c); the final cumulative deaths would be ninefold greater than the current situation (Fig. S5f in the Supplementary Document). Moreover, reducing face mask usage would not only increase the magnitude of a future surge but also lead to an earlier peak time (Figs. 2c and 3c).

Impact of various combinations of face mask usage and contact rate

Fig. 4 and Fig. S6 demonstrated a similar pattern of the impact of combined face mask usage and contact rate on the likelihood of a major surge of COVID-19 after reopening. The figures showed that regardless of the reopening date, a high contact rate would always need to be matched with a high face mask usage to avoid a future surge. After reopening, if the contact rate were maintained at 70% of the prepandemic level, a relatively low face mask usage (30%) would be sufficient to prevent a future surge. In contrast, if the contact rate was at 90% of the prepandemic level, 65% face mask usage was necessary to prevent a future surge. Furthermore, if the contact rate increased to the prepandemic level, at least 75% face mask usage was necessary to prevent a future surge. It is worth noting that if “revenge travel” occurred and the contact rate increased to 165% of the prepandemic level, a major surge of COVID-19 would always occur regardless of face mask usage.

Discussion

Our model projected that if all the control measures were relaxed, a major surge of COVID-19 would occur, and deaths due to COVID-19 would increase by nearly 10 times. Our results showed that it is important to maintain social contact rate lower than 80% of the prepandemic level but also ensure 50% of the population wore face masks. If the contact rate returned to 100% of the prepandemic level, face mask usage would need to be maintained at nearly 80% to prevent a major surge. Our results also showed that delaying reopening will only delay the peak of the surge but not reduce the magnitude of the pandemic if the other control measures stay constant. In other words, only if face mask usage and social distancing were strengthened can delaying reopening reduce the magnitude of the pandemic.

Maintaining a certain level of social distancing is necessary to prevent a future surge of COVID-19 after reopening the city. Recent studies based on mathematical modeling indicated that the government-initiated social distancing alone only had a short-term impact on the pandemic.[22,23] It will unlikely eradicate the epidemic but only enable a better preparation of the health care system for the major surge. Self-imposed social distancing by the population, in contrast, is more likely to be sustainable in reducing the transmission of the virus. Consistently, mass communication and social media to improve public awareness on COVID-19 prevention and control even after reopening should be promoted. If essential economic events, large group gatherings, and business activities involving physical person-to-person contacts cannot be avoided, maintaining social distancing during these activities would help reduce viral transmission.

Face mask usage in public settings after reopening should remain in place. The latest evidence showed that face mask use could result in a large reduction in the risk of infection, even in non-healthcare settings.[20] Our finding demonstrated that a higher contact rate after reopening required a higher face mask use correspondingly. For incidence, if the contact rate after reopening can be maintained at 70% of the prepandemic level, only 30% of face mask usage is sufficient to prevent a major surge of COVID-19. However, if the contact rate after reopening was 90% of the prepandemic level, face mask usage needs to be maintained at 65% to prevent a major surge. The required coverage needed to be 75% if the contact rate returned to the prepandemic level. With this consideration, the requirement of face mask use in public settings, such as public transportation, supermarkets, and shopping centers, is likely necessary.

We found that nearly two-thirds of infections were transmitted by the presymptomatic and asymptomatic individuals, and face mask usage does not seem to change this proportion. This is consistent with the recent findings that a large proportion of infected individuals did not show any symptoms when they were actively tested for COVID-19. As a result, the proportion of infection caused by pre-asymptomatic and symptomatic individuals may account for most of the infections, as demonstrated by our model. Interventions for symptomatic individuals are relatively straightforward; timely isolation and contact tracing are effective means to reduce the further spread of the virus.[24] In contrast, for presymptomatic and asymptomatic individuals, prevention of viral transmission would be more difficult. We argue that the use of a face mask would be an effective way to prevent presymptomatic and asymptomatic individuals from transmitting the virus to others and, thus, persistent use of face masks after reopening should be promoted.

Although a mathematical model cannot fully capture the complexity of a reopening plan, it can shed light on the potential consequences resulted from reopening the economy. For example, a region would be fully reopened after Phase 4 of the reopening plan, which means the contact rate among people may resume to the prepandemic level. In this case, the model can provide information on what control measures would be needed to prevent a major surge of COVID-19.

Although results reported in this study are based on NYC, the modeling approach and main takeaways could be translated to other cities if additional steps were taken. First, other cities in the United States are smaller and less dense than NYC; care should be taken in estimating model parameters such as the contact rate to reflect the characteristics of the city. Second, when the model is used to predict the trajectory of the pandemic in another city, it needs to be recalibrated based on the local data. Third, other cities may implement control measures (e.g. face mask mandate) on a different date from NYC, which needs to be fully considered in the new model. In addition, the findings from this study could be used to inform control measures for potential other pandemics. More specifically, non-pharmaceutical interventions such as social distancing and face mask use should play a central role in controlling other pandemics, especially when vaccines are not available. Even after effective vaccines have been rolled out, social distancing and face mask use would still be needed to control the pandemic more effectively, as demonstrated in a recent study.[16]

Our study has several limitations. First, we assumed a homogeneous population, but human behaviors tend to vary substantially. It is evident that social contact and self-imposed prevention behaviors have varied substantially in the population. Second, the current understanding of the infectiousness of the presymptomatic and asymptomatic individuals are still limited. In our study, we assumed the transmission rate among presymptomatic and asymptomatic individuals was approximately 25% of those who are symptomatic, which needs to be supported by more evidence. Third, the model did not take into consideration population mobility within the city during the pandemic. Fourth, the study did not specifically investigate the resumption of intercity or international travel but assumed that residual cases in the city would essentially have the same effect as people traveling in and out. Fifth, we did not evaluate the economic implications of the lockdown and benefits from a controlled epidemic. Sixth, the confirmed number of COVID-19 cases reflects the level of testing available in a population. As testing is not optimal in NYC, it is likely that we underestimated the number of cases in all scenarios. Finally, we estimated model parameters from both the literature and a model calibration process when the relevant literature is not available. Model parameters estimated based on the model calibration process tended to have narrow CIs, which may not reflect the reality. Despite these limitations, our model is well-calibrated using local data and, thus, can be used to inform pandemic mitigation strategies.

Conclusions

A better understanding of the complex relationship between reopening the economy and implementing control measures is needed to control the COVID-19 pandemic and prevent a major surge in the future. The findings from our study can shed light on this complex relationship and help policymakers identify the conditions under which a city can be reopened safely.

Author statements

Acknowledgements

This work was supported, in part, by the National Natural Science Foundation of China (81950410639 [L.Z.], 12171387 [M.S.], 11801435 [M.S.], 11631012 [Y.X.], 11971375 [J.Z.]); Outstanding Young Scholars Support Program (3111500001 [L.Z.]); Xi'an Jiaotong University Basic Research and Profession Grant (xtr022019003 [L.Z.] and xzy032020032 [L.Z.]) and Xi'an Jiaotong University Young Scholar Support Grant (YX6J004 [L.Z.]); Bill & Melinda Gates Foundation (20200344 [L.Z.]); China Postdoctoral Science Foundation (2018M631134 and 2020T130095ZX); the Fundamental Research Funds for the Central Universities (xjh012019055, xzy032020026, and xzy032020027). Young Talent Support Program of Shaanxi University Association for Science and Technology (20210307), Natural Science Basic Research Program of Shaanxi Province (2019JQ-187, 2019JM-273); Xi'an Special Science and Technology Projects on Prevention and Treatment of Novel Coronavirus Pneumonia Emergency (20200005YX005); Science Foundation for COVID- 19 of Xi'an Jiaotong University Health Science Center and Qinnong Bank (2008124); Zhejiang University special scientific research fund for COVID-19 prevention and control (2020XGZX056). L.R. was supported by National Science Foundation (DMS-1950254). The contents of this paper are solely the responsibility of the authors and do not necessarily represent the official views of the funding institutions.

Ethical approval

This study only used publicly available data, so ethical approval was not required.

Competing interests

None.

Disclosures

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.puhe.2021.09.005.

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