Summary

In the battle against COVID-19 pandemic, non-pharmaceutical interventions (NPIs) are critical to mitigate the spread of the virus before targeted therapeutics become available. The measures, stringency, and duration of the interventions are key factors to contain the virus and minimize the deaths. However, it is difficult for policy makers to make choices due to the lack of quantitative assessment. Here we propose a novel model by introducing a policy intensity factor into the pandemic progressing model, allowing for the assessment of NPIs. We project the pandemic durations and the final affected cases for the top 15 economies across the globe under their currently imposed NPIs. Our results suggest that the countries implementing strong NPIs can end the pandemic in 3-4 months, and countries implementing light NPIs may end the pandemic in 9-12 months. We also found that the number of affected people can be overwhelming with a 3-month implementation of light NPIs. For countries currently imposing light NPIs, 6-12 months are necessary to keep the affected number of people to 1% of the population. We anticipate the correlation between the stringency of NPI and the policy intensity factor provides a new insight into the decision-making process.
Projecting and comparing non-pharmaceutical interventions to contain COVID-19 in major economies

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Non-pharmaceutical interventions (NPIs) such as quarantine, self-isolation, social distancing, and virus-contact tracing can greatly reduce the spread of the virus during a pandemic. In the wave of the COVID-19 pandemic, many countries have implemented various NPIs for infection control and mitigation. However, the stringency of the NPIs and the resulting impact among different countries remain unclear due to the lack of quantitative factors. In this study we took a further step to incorporate the effect of the NPIs into the pandemic dynamics model using the concept of policy intensity factor (PIF). This idea enables us to characterize the transition rates as time varying quantities instead of constant values, and thus capturing the dynamical behavior of the basic reproduction number variation in the pandemic. By leveraging a great amount of data reported by the governments and the World Health Organization, we projected the dynamics of the pandemic for the major economies in the world, including the numbers of infected, susceptible, and recovered cases, as well as the pandemic durations. It is observed that the proposed variable-rate susceptible-exposed-infected-recovered (VR-SEIR) model fits and projects the

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pandemic dynamics very well. We further showed that the resulting PIFs correlate with the stringency of NPIs, which allows us to project the final affected numbers of people in those countries when their current NPIs have been imposed for 90, 180, 360 days. It provides a quantitative insight into the effectiveness of the implemented NPIs, and sheds a new light on minimizing both affected people from COVID-19 and the economic impact.

Introduction

The World Health Organization (WHO) declared the new coronavirus, identified as COVID-19, as a pandemic due to its fast rate of spread around the globe. As of May 15 2020, the outbreak of the virus has already generated 4,338,658 cases and 297,119 deaths globally. The numbers of infections and deaths, as well as the economic disruptions are much more severe than those caused by SARS-CoV in 2002-2003 (8,906 infections and 774 deaths). A short-term spike of the number of cases can temporarily overwhelm the healthcare capacities in well-resourced countries. Even worse, results from Ref. indicate that the COVID-19 may exhibit spiral and seasonal patterns of the outbreak. Ending the global COVID-19 pandemic requires not only the effective pharmaceutical interventions, which are not expected to be available for months given the current medical knowledge (e.g., the hosts and transmission potential still remain unclear), but also the implementation of effective non-pharmaceutical interventions (NPIs). It has been confirmed that human-to-human transmission primarily occurs through respiratory droplets. It can also occur through contact with contaminated surfaces such as stainless steels and plastics. Existing evidences have shown that NPIs including physical distancing and travel restrictions etc. would significantly change the social mixing patterns and reduce effective
interactions between infected and susceptible individuals, hence interrupting the transmission from susceptible to exposed \(^{11-14}\). Recent reports \(^{8,11,12}\) suggest that NPIs can also delay the peak of the infection curve and ease the abrupt burden on healthcare systems. So far various non-pharmaceutical interventions have been implemented to contain the spread of the virus and mitigate the cross-infection, such as inter-city travel restrictions, self-isolations, quarantine, social distancing, wearing face masks, travel- and contact-tracing, mass gatherings bans, etc. These NPIs measures aim to reduce the transmission rate, flatten out the epidemic curve, reduce the peak demand on healthcare services, and buffer more time for vaccine development.

One of the governmental decision difficulties in battling the COVID-19 pandemic is to determine which NPIs are optimal and how stringent those NPIs should be implemented. Since there are no targeted therapeutics nor effective vaccines \(^8\), the long-term NPIs can render a high economic loss and social disruptions. Minimization of deaths from COVID-19 virus and the economic impact of virus spreading cannot be achieved at the same time, as human and human-interaction are the pillars of economy health and growth. Once imposing the stringent NPIs such as city lockdowns and travel bans, the economy can be heavily affected. As the WHO Director-General noted, at the mission briefing on COVID-19 on March 12 2020, that “all countries must strike a fine balance between protecting health, preventing economic and social disruption, and respecting human rights”\(^{15}\).

Predictive mathematical model for epidemics can be a key to understand the COVID-19 spreading dynamics, providing a quantitative insight for the estimation of the medical requirements and capacities. It can also help to prevent, detect, treat or cure COVID-19 \(^{16}\). The susceptible-infected-recovered (SIR) model and its variants (reduced or enriched) are
the most commonly-used ones for human-to-human transmission modeling \textsuperscript{17-20}. Regarding the predictive modeling of COVID-19, Koo et al. used an agent-based influenza epidemic simulation model (FluTE) to estimate the likelihood of human-to-human transmission in Singapore, and found that the estimated median number of infections was greatly reduced (99.3\%) by NPIs in a relatively mild outbreak \textsuperscript{12}. Wu et al. predicted the number of infections in Wuhan from Dec 1 2019, to Jan 25 2020 \textsuperscript{21} using the susceptible-exposed-infected-recovered (SEIR) model, and they further estimated the overall symptomatic case fatality risk of COVID-19 in Wuhan \textsuperscript{22}. In those models, the fundamental quantity of basic reproduction number ($R_0$) governs the transmission dynamics. The basic reproduction number is either assumed or estimated using existing data as a constant. Dehning et al. applied the Bayesian change point analysis in the spread of COVID-19 with the SIR model \textsuperscript{13}. The change point analysis identified the sudden changes of $R_0$ in the context of Bayesian hypothesis testing, making the value of $R_0$ a piecewise constant in the knotted intervals during the course of pandemic progressing. The quantity $R_0$ is the combination of the virus inherent contagious capacity as well as the social network structure. Without interventions, the connectivity and contact rates of the whole population remains stable statistically as a whole and the inherent properties of the virus hold unchanged. Under such conditions $R_0$ determines (together with other variables and initial values) the dynamical development of the pandemic. However, in the COVID-19 pandemic under stringent NPIs, we must consider the great influence of those governmental and individual actions on the effective $R_0$.

Towards resolving the existing difficulties in making reliable projections, we took a further step to propose a time-varying SEIR model based on the two fundamental facts
observed so far, (1) the effective basic reproduction number is highly correlated with the NPI measures and its stringency, and (2) the effective basic reproduction number varies with time. The former fact is clear, the past and ongoing experiences of China, South Korea, and Italy on reducing the total number of cases and containing the spreading are encouraging, comparing with other countries with more relaxed implementations of NPIs. We incorporated this fact by introducing the concept of policy intensity factor (PIF) into our model. The latter fact is well established and acknowledged. No matter using fixed time-interval regression or change point analysis-guided updating, the attempt is made to align the model’s projection with the observation data by adjusting the $R_0$-value. We admitted this time-varying nature of $R_0$ by modeling it as a time-dependent variable, with a declining rate correlated with the PIF. By doing so, the effectiveness of NPIs can be quantified, and thus providing an assessment to guide decision-making for the implementation of NPIs.

The rationality of the inductive construction of the proposed model requires us first to look closer at the current NPIs. The specific measures of NPI, including governmental actions and individual actions, the stringency of their implementations at both the governmental and individual levels, as well as the underlying reasons that make the overall effect different in containing the spread of COVID-19 virus. After that, we presented the proposed model, together with the details on how the projection is made. By leveraging the abundant public accessible data from WHO, we projected the courses of COVID-19 progressing in the top 15 economies of the world in terms of numbers of infected, susceptible and recovered cases. We also projected the pandemic durations and the final affected proportions of the populations in those countries. We observed a good correlation
between our proposed policy intensity factor and the stringency of NPIs, making it a proper quantity to evaluate the effectiveness of the NPIs implemented by the governments.

**NPI measures**

In general, we can divide the NPI measures into two categories, individual actions and governmental actions. The governmental actions require a systematic policy-making process and a top-down supervised implementation strategy; therefore, the governmental actions can be executed with different degrees of stringency, and the individual actions are usually suggested or encouraged as public advices. We summarized the typical government actions implemented and individual actions advised by epidemic experts in Table 1.

**Governmental and individual actions**

Governmental actions implemented by many countries in dealing with COVID-19 pandemic include, but may not be limited to, nationwide large-scale testing, virus-contact tracing, population flow tracing, town or city lockdown, border control, closure of schools and workplaces, and mass-gathering bans.

Quarantine plays an exigent role in the process of mitigating the spread of the virus, especially for countries with high population densities in large cities. Scientific evidence shows that the incubation periods for other types of coronaviruses are between 1 and 14 days. Recent reports indicate that the median observed incubation period for COVID-19 is 5 days with the 95% confidence interval of 4.5-5.8 days, and 97.5% of those who get infected show symptoms within 11.5 days with a 95% confidence interval of 8.2-15.6 days. The observation and statistical estimation form the basis of making the 14-day self-isolation policy for those who travel from virus-impacted regions with a potential virus-contact history.
The closure of workplaces, universities, schools, daycare centers, non-essential businesses and stores are alternative governmental means to reduce person-to-person contact. Although the detailed contributions from each individual measures are not yet clear given current COVID-19 data, these measures must be implemented in conjunction with effective personal actions, for example, staying at home, avoiding unnecessary trips, eliminating group activities and mass gathering; otherwise, the governmental actions will not achieve the maximum mitigation strength.

Another governmental action is the implementation of nationwide virus-contact tracing and travel history tracing for those who develop symptoms. With the help of personally shared map and navigation data as well as the telecommunication location service data, the travel and contact history of a confirmed case can be used for backward tracing. The possibly affected people can be identified for further test, isolation, and treatment. In China, temperature testing at the entrance of public buildings and residential communities are also mandatory, providing a massive coverage in detecting the potential symptoms.

Individual actions such as wearing face masks, keeping social distance, reducing non-essential trips, staying at home, working from home, washing hands frequently, and so on, are equally important in mitigating the spread of virus during the pandemic. Without individual actions, the effectiveness of governmental actions will be largely reduced.

**The stringency of NPIs**

The different measures are just one dimension of the NPIs. The stringency in terms of mandatory actions is another dimension worth mentioning. The stringency can loosely be defined as whether the actions are mandatory or suggested.

Based on the stringency of the implementation of NPIs, countries with the COVID-19
outbreaks can be divided into three categories, namely, strong non-pharmaceutical interventions (S-NPI); moderate non-pharmaceutical interventions (M-NPI) and light non-pharmaceutical Interventions (L-NPI). We grouped the top 15 economies of the world into the three categories accordingly in Table 1. The intervention timing refers to the time imposing the strictest NPI measures such as city lockdowns.

For the countries in the category of S-NPI, China implemented the stringent NPI measures to mitigate the spread of COVID-19 virus. Since January 23, Wuhan had been locked down and more than 30,000 medical staff from all over the country were mobilized to Hubei battling the virus as of Feb. 17. The lockdown was also imposed on many cities in Hubei Province with inter-city travel bans. In dealing with the potential diffusion of the virus through the mass flow, China also rolled out the contact-tracing using mobile apps. It allows to analyze the travel history and provide up-to-date status report on smartphones, and ensures that almost end-to-end (departure-arrival locations) and targeted isolation can be made on demand. The nationwide NPIs in China also include the closure of the daycare centers, schools, universities, the postpone of back to work for nonessential workers after the Chinese New Year holiday. Everyone travelling to and from epidemic-stricken cities are subject to 14-day at home self-isolation before participating other activities. The entries to residential communities, grocery stores, workplaces and other public places are all subject to temperature screening and the requirement of wearing face masks. South Korea was the first countries to provide a drive-through testing system, and it also has the virus-contact tracing system. Italy imposed a nationwide lockdown from 10 March, with only grocery and drug stores open to public. Travels for valid reasons require the permission from police department.
In the category of M-NPI, French throughout the country were required to stay at home except those who purchase necessities and seek medical and healthcare services from March 16. Germany also implemented the statewide policy on restricting people from going out for unnecessary activities. Schools and daycare centers were closed and gatherings were banned. In Spain, people throughout the country were not allowed to leave their homes except under certain circumstances from March 14.

For L-NPI countries, the US has the first confirmed case of COVID-19 reported from Washington State on January 31, 2020. Soon after, California and Washington reported outbreaks. At this moment the cases in the US exceed cases reported in China and Italy combined. Different states and major cities have imposed different policies. In states and cities that are greatly impacted by the virus, e.g., NYC and New Jersey, staying at home was suggested and most companies asked their employees to work from home. Schools and daycare centers were also closed. Recently New York State doubled testing capacity to reach 40,000 diagnostic tests per day with more than 700 testing sites. Residents of New York were encouraged to get tested at nearby testing sites. The state also implemented the Contact Tracing Program to help slow the spread of COVID-19 and ease the social isolation without triggering renewed virus spreading. In UK, isolating towns or cities was not part of the British government plan at the beginning of the COVID-19 outbreak, in hope of a degree of herd immunity can help to reduce and broaden the peak. Given the rapid development of the epidemic and the quickly growing number of infected people, the British government imposed the lockdown strategy in mid-March, with only essential trips to medical centers and grocery stores, and exercise, allowed. The government asked the citizen to stay at home as much as possible, work from home if that is possible, limit the
contact with other people, keep 2-meter distance apart when going out. The government also published a guidance on April 15 for COVID-19 test by-appointment for their essential workers. Australia declared on March 19 that non-Australian citizens were not allowed to enter the country. Some states closed their non-essential business places from March 22. Japan imposed travel restrictions in many areas starting from March 26.

Results

We projected the infection curve, the pandemic duration, the susceptible and recovered curves. Results of the top 15 GDP countries according to the International Monetary Fund (2019 estimates) database are shown in Table 2. It is observed that the VR-SEIR model fits and projects the data consistently for all the participating countries. Taking the results of China as an example, the projected duration is 104 days since January 1, 2020 (27 cases), and the end of the pandemic in China is April 15 by our model. This result is consistent with the fact that from the projected end April 15, 2020 (83356) to May 15, 2020 (84038 cases), the new cases after our projected end is less than 0.8% of the total cases. The projected recovered case (including deaths) number is 87279, which agrees with the actual number of 83918 recovered cases (including deaths) as of May 15, 2020.

Based on our model projections, three to six months of pandemic durations are expected for countries implementing S-NPI such as China (104 days), South Korea (117 days), and Italy (161 days). Eight to ten months of durations in general are expected for the countries with mild NPI such as US (308 days), UK (309 days), and Canada (207 days). The current data also show that the numbers of infection cases in China, South Korea, Japan, Italy, Germany, France, Spain, and Australia already passed the plateaus of the infection curves. In particular, the numbers associated with China, South Korea, Germany,
and Australia are falling quickly to reach the bottom of the curves, approaching the end of the pandemic outbreak.

The model allows us to quantify the strength of NPIs imposed by different countries using the PIF ($\lambda$). The quantitative evaluation of NPIs can be leveraged to help decision-makings at the early stage of the epidemic. This advantage has not been realized using the classical SEIR model. According to our results, the S-NPI corresponds to the range that $\lambda > 0.05$, M-NPI corresponds to $0.03 < \lambda \leq 0.05$, and L-NPI is correlated with the range of $\lambda \leq 0.03$, as shown in Fig. 1.

**Fig. 1 The Correlation between the stringency of NPIs and policy intensity factor $\lambda$.**

In Fig. 4, we presented the projected variation of the effective basic reproduction number along with time. For countries in the category of S-NPI, the resulting $R_0(t)$ curves have the steepest decreasing rate at any time instance. Based on several early reports, the $R_0$ value of China is assumed to have a baseline number between 2 and 2.6. $^8, 14, 35, 36$ For China, combined governmental actions and individual actions have aided in lowering the
value of $R_0$, as a result and the updated $R_0$ has declined by at least 50-60\% \cite{8}, with a regional reduction by 85\% in Shenzhen \cite{37}. The reduction in $R_0$ agrees with the projections given by our model. For example, the model projects the effective $R_0(t)$ in China declines from the initial value of 1.88 (day 1) to 0.18 and 0.02 at day 30 and 60, respectively.

The mechanism of epidemic progressing suggests the basic reproduction number decreases until it falls below one when the infection reaches and passes the plateau of the infection curve, either due to the NPIs or the exhaustion of susceptible people. Considering the current shortage of effective medicines and vaccines, this reduction in $R_0$ can be largely attributed to the implementations of NPIs.

We further projected the final affected number of people in the countries. The projection results on the pandemic duration as well as the final affected percentage of the population for the 15 countries were presented in Fig. 2. The size of the circles represents the percentage of the population affected. We also showed correlation between the PIF, $\lambda$, and the pandemic duration. It can be observed that the pandemic durations for S- and M-NPI countries are in general shorter than countries in L-NPI, and the strong NPIs can greatly reduce the proportion of the affected in the whole population. We also found that the number of affected people can be overwhelming with a 3-month implementation of light NPIs. For countries currently imposing light NPIs, 6-12 months are necessary to keep the affected number of people to 1\% of the population.
Fig. 2 The projected pandemic duration and the final affected fraction of the total population.

Experiences with 1918-19H1N1 influenza pandemic have shown that NPIs have significant effects on reducing the amount of people been infected. Several cities in US adopted a variety of NPIs such as, the closure of school and work place in that pandemic. However, transmission rebounded once controls were lifted. This phenomenon indicates that the early termination of NPIs may cause a rebound of the pandemic even with stringent policies.

To investigate the potential impact of the NPI duration in the countries, the total number of affected people given three different NPIs durations of 90, 180, and 360 days are projected. The detailed results of the affected fraction of population were presented in Fig. 3. The projection results indicated that for S-NPI countries, a short-term (90 days) implementation can be an effective and efficient means to cease the spreading of the virus.
and reduce the number of affected people. For L-NPI countries, a long-term implementation is necessary to reduce the total number of affected people.

**Fig. 3 The final affected fraction of the total population when their current NPIs have been imposed for 90, 180, and 360 days.**

In summary, battling the epidemic is a system engineering in the nationwide scale and magnitude. Throughout the history of battling unknown deadly viruses, medical treatment and non-pharmaceutical interventions are almost equally important. In particular, when no effective medicines and vacancies are available in time, non-pharmaceutical interventions can be the key to mitigate the spread of the virus and reduce the overall mortality rate.

Basing on the stringency of the NPIs implemented in several countries, we grouped the countries into three categories, namely strong NPIs (S-NPI), moderate NPIs (M-NPI), and light NPIs (L-NPI). We took a further step and proposed a novel variable rate susceptible-
exposed-infected-recovered model (VR-SEIR) by introducing the concept of policy intensity factor. The model allows us to capture the dynamical behavior of the basic reproduction number of COVID-19 under the influence of NPIs.

By leveraging a great amount of data reported by governments and WHO (as of May 15, 2020), we projected the epidemic dynamics for the top 15 economies of the world in detail, including the numbers of infected, susceptible, and recovered, as well as the pandemic duration. Based on the model projection results, we observed a correlation between the three levels of NPIs and the policy intensity factor \( \lambda \). It was further noted that this quantity provides a means to evaluate the effectiveness of current NPIs implemented in those countries.

We observed from the data and model projection, that the countries with stringently implemented NPIs can greatly help to slow the spread of the virus and reduce the overall infection cases, comparing with the countries with relaxed implementations of NPIs. The countries in the category of S-NPI already passed the plateaus of the infection curves, while the countries in M-NPI and L-NPI are still in the phases of flattening and broadening the peaks. The governmental and individual actions in the S-NPI countries can provide invaluable experiences in winning the global pandemic battle. Considering the current shortage of effective medicines and vaccines, the declining of the basic reproduction number can be largely attributed to the implementations of NPIs.

However, the economy can be greatly impacted due to the implementation of nationwide stringent NPIs. For example, the most effective governmental measures such as city lockdown, self-isolation, closure of work places and schools, inter-city travel bans, border control and so on, may cause serious social and economic burdens. The
International Labor Organization (ILO) estimates the job loss due to the COVID-19 epidemic may reach 25 million \(^4\). Achieving the delicate balance between the mitigation measures and the economy impact is highly nontrivial.

As noted in Ref. \(^{14}\), “personal, rather than government action, in western democracies might be the most important issue”. It is no doubt that personal responses to the governmental actions will be crucial to control the spread of COVID-19 in an outbreak. This may explain countries with different cultural backgrounds may implement those top-down governmental actions at various magnitudes and scales. Our finding suggested that the number of affected people will be overwhelming with only 90 days implementation of L-NPI. The personal responses inevitably affect the NPI measures. It is the governments’ duty to provide the guidance and encouragement for the public to implement those NPIs more voluntarily without causing anxiety and social disruptions, which might be the issue we need to face after the wave of the COVID-19 pandemic.

One caveat is worth mentioning that the stringency of the NPIs are divided into three levels, and the contributions from each specific intervention measures such as closure of schools, travel- and contact-tracing, etc., are not clear. Further investigations on the detailed contributions of those measures can help the governments implement the NPIs more effectively. Our model can incorporate those specific measures. For example, consider two intervention measures, and we can rewrite Eq. (1) as \(\frac{dR}{dt} = -(\lambda_1 + \lambda_2) R\), where \(\lambda_1\) and \(\lambda_2\) are the corresponding PIFs of the two measures. In our model, a four-state \((S, E, I, R)\) infection chain is used. It is known that the infection chain can be decomposed into more intermediate or detailed states. For example, the infected can be divided into “symptomatic infected but undetected” and “diagnosed” sub-states \(^3\). The concept of PIF can also be
adopted to a model with more state variables. Thus, when such detailed survey data become available, these states can directly be incorporated in the VR-SEIR model.

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## Table 1 Measures and stringency of NPIs implemented in the top 15 economies.

| Countries | Intervention measures | Intervention timings |
|-----------|-----------------------|----------------------|
|           | A    | B    | C    | D    | E    | F    |                   |
| S-NPI     |       |       |       |       |       |       |                   |
| China     | √    | √    | √    | √    | √    | √    | < 3 weeks         |
| Korea, South | √    | √    | ✗    | √    | √    | √    | < 3 weeks         |
| Italy     | √    | √    | √    | √    | √    | √    | < 5 weeks         |
| M-NPI     |       |       |       |       |       |       |                   |
| France    | √    | ✗    | √    | √    | √    | √    | < 6 weeks         |
| Germany   | √    | √    | √    | √    | √    | √    | < 6 weeks         |
| Brazil    | √    | ✗    | √    | √    | √    | √    | < 9 weeks         |
| Spain     | √    | ✗    | √    | √    | √    | √    | < 8 weeks         |
| Australia | √    | √    | √    | √    | √    | √    | < 8 weeks         |
| L-NPI     |       |       |       |       |       |       |                   |
| Japan     | √    | ✗    | √    | √    | √    | √    | < 8 weeks         |
| US        | √    | √    | ✗    | √    | √    | √    | < 6 weeks         |
| Canada    | √    | ✗    | √    | √    | √    | √    | < 7 weeks         |
| India     | √    | ✗    | √    | √    | √    | √    | < 8 weeks         |
| UK        | √    | √    | ✗    | √    | √    | √    | < 8 weeks         |
| Mexico    | √    | ✗    | ✗    | √    | √    | √    | < 5 weeks         |
| Russia    | √    | √    | √    | √    | √    | √    | < 9 weeks         |

A: Quarantine and Self-isolation; B: Large-scale testing and tracking; C: Citywide lockdown; D: School, workplace closures; E: Wearing face masks; F: Minimize Social activity. Intervention timing in the table refers to the time to take the most severe NPI (like citywide lockdown) on a wide scale. The timing of taking other different NPIs was not differentiated. Citywide lockdown includes restricting entering or leaving the city, closing public places or restricting people from going out.
Table 2 Model projection of the susceptible, infected, recovered cases, and the pandemic duration.

|          | Infected (num. of ppl.) | Susceptible & Recovered (num. of ppl.) |
|----------|-------------------------|----------------------------------------|
| Infected |                         |                                        |
| US       | ![Infected Graph](#)    | ![Susceptible & Recovered Graph](#)    |
| CA       | ![Infected Graph](#)    | ![ Susceptible & Recovered Graph](#)   |
| CHN      | ![Infected Graph](#)    | ![Susceptible & Recovered Graph](#)    |
| KR       | ![Infected Graph](#)    | ![Susceptible & Recovered Graph](#)    |
Fig. 4 Variations of the effective basic reproduction number $R_0(t)$ along with time under current NPIs with major governmental actions noted.
Methods

The variable rate SEIR model (VR-SEIR)

A commonly-used epidemiological term characterizing the evolution of the virus diffusion in population is the basic reproduction number ($R_0$). It defines the mean number of secondary cases generated by one primary case given that the population is largely susceptible to infected. Using a simple susceptible-infected model, a quick estimate of the final fraction of the population being infected, without any mitigation, is approximately $1 - 1/R_0$. Given the early stage data of the epidemic, $R_0$ was estimated as 2-2.6, about 50%-60% of the population would become infected. However, $R_0$ is expected to decline as more and more efforts are made to mitigate the spread of the virus.

We adopted the classical infection chain, consisting the four major stages of susceptible (S), exposed (E), infected (I), and recovered (R), collectively termed SEIR. The recovered state includes healed and unhealed (death) individuals. Here we took a further step to propose a variable rate SEIR (VR-SEIR) model. Based on the idea of the principle of maximum entropy, we assumed that the basic reproduction number declines along time with a rate proportional to its current value. Mathematically, this assumption allows us to write the time-varying basic reproduction number as

$$\frac{dR}{dt} = -\lambda \cdot R,$$

where the parameter $\lambda$ is the decay constant, and $t$ is the time variable. The solution to Eq. (1) is

$$R(t) = R_0 \exp (-\lambda t),$$

$$\text{(2)}$$
where $R_0$ is the initial value at $t = 0$. The parameter $\lambda$ characterizes the dynamical behavior of $R$ under the influence of NPIs. Therefore, we call this parameter policy intensity factor (PIF).

By introducing the so-called policy intensity factor (PIF), we can incorporate the influence of the NPI measures on the basic reproduction number, and obtain the following variable-rate SEIR model,

\[
\begin{align*}
\frac{dS}{dt} &= -a_0 \exp(-\lambda t) IS/N \\
\frac{dE}{dt} &= a_0 \exp(-\lambda t) IS/N - \alpha E \\
\frac{dI}{dt} &= \alpha E - \gamma I \\
\frac{dR}{dt} &= \gamma I
\end{align*}
\] (3)

Different from the existing SEIR model and its variants, the transition rate of $S \rightarrow E$ in our model Eq. (3) becomes a continuous time-dependent variable, \[\beta(t) = a_0 \exp(-\lambda t),\] (4)

in contrast to a constant in existing models. The quantity $a_0$ can be thought as the initial rate of infection ($t = 0$), reflecting the inherent contagious rate of the virus. Variables $S$, $E$, $I$, $R$ are the numbers of people in the four states, respectively, and $N$ is the number of total population. The model reduces to conventional SEIR model by setting $t = 0$.

In addition, we have the effective basic reproduction number of the virus under the
influence of NPIs

\[ R_0(t) = a_0 \exp(-\lambda t) / \gamma = R_0 \exp(-\lambda t), \]  

noting that the original constant basic reproduction number \( R_0 \) is defined as the ratio of the constant transition rate of \( S \to E \) over that of \( I \to R \) \(^{43}\).

**Pandemic duration**

With the proposed VR-SEIR model, we defined the pandemic duration as the time duration from the day having the first case of infection, \( T_0 \), to the ending of the spread of the virus. The end day of the pandemic can be determined in the following measures. In our VR-SIER model, the time-dependent basic reproduction number, \( R_0(t) \), in Eq. (5), determines the dynamics of the infection and decays with time. The convergence of the numbers of people in the four states can be warranted when \( R_0(t) \) decays to a small number \( \varepsilon \). For example, a value of \( \varepsilon = 0.1\% \) or \( \varepsilon = 1\% \) usually ensures the convergence of the VR-SEIR model, indicating the end of the pandemic. Given that \( R_0(t) \) decays to a small value of \( \varepsilon \), we can find the projection of the pandemic duration using Eq. (5) as,

\[ \Delta T_R = T_{end,R} - T_0 = -\frac{1}{\lambda} \ln \left( \frac{\varepsilon \gamma}{a_0} \right). \]  

Another criterion can be used to define the duration of the pandemic is the double or single-sided \( \alpha \)-quantile (e.g., 95\%) interval of projected infection curve \(^{12}\). Using the quantile approach, we can define the end of pandemic as

\[ \Delta T_\alpha = T_{end,\alpha} - T_0 = F^{-1}_\alpha(\hat{I}), \]  

where \( \hat{I} \) is the projected number of infected people, and \( F^{-1}_\alpha(\hat{I}) \) is the \( \alpha \) - quantile of the cumulative summation of the projected number of infected people.

Without the loss of generality, in this study, we define the projected pandemic duration
as the minimal value between the two quantities.

\[ \Delta T = \min \{ \Delta T_R, \Delta T_q \} \quad (8) \]

where \( \varepsilon = 1\% \) and \( \alpha = 0.95 \) are used to project the pandemic duration throughout this study.

**Projection of affected people and pandemic duration**

The COVID-19 data (as of May 15, 2020) of the top 15 economies in the world are obtained. We use the data to estimate the model parameters \((a_0, \lambda, \alpha, \gamma)\) by minimizing the difference between the model projection and the actual numbers of the four states using the method of least squares. In both parameter estimation and projection, we used one-day interval as the time-step since it is the maximum time resolution in the data. In projection, we assumed that the natural birth and death are relatively stable; therefore, the total population \(N\) does not reflect the natural birth and death during the projection. The initial values (I.V.) of \((S_0, E_0, I_0, R_0)\) for the state variables \(S, E, I, R\) are set accordingly as follows,

\[
\text{I.V. } \rightarrow \begin{cases}
I_0 &= I(1) \\
E_0 &= I(7) \\
R_0 &= 0 \\
S_0 &= N - I_0 - E_0 - R_0
\end{cases}, \quad (9)
\]

where \(I(1)\) is the reported number of confirmed cases on day 1 in the record. The initial value of \(E_0\) is set to the infected number of people on day 7, \(I(7)\), representing the fact that the infected people are all due to the exposure to the virus with an average of 7-day time lag before developing symptoms. The total population, \(N\), is taken from the demographic

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1 The survey data source of China is National Health Commission (NHC). The survey data outside China are World Health Organization (https://www.who.int/emergencies/diseases/novel-coronavirus-2019) and John Hopkins University & Medicine, Coronavirus Resource Center (https://coronavirus.jhu.edu/map.html). The data are collected and published by Tencent Inc., via the webpage: https://news.qq.com/zt2020/page/feiyan.htm#/global
census and held constant in projection as mentioned above. The dynamical evolution of the state variables is computed using a day-by-day incremental scheme according to Eq. (3).

The final affected number of people is defined as the number of the total population subtracted by the number of susceptible people. The condition “final” refers to the fact that the pandemic dynamical equation converges. Since the numbers of total populations among the countries are different, we used the proportion of affected in the whole population in terms of percentages,

\[ A_f = \left(1 - \frac{\tilde{S}}{N}\right) \times 100\%, \quad (10) \]

where \( N \) is the total population of the country, and \( \tilde{S} \) is the value when the VR-SEIR model converges, i.e., \( S(t) \to \tilde{S} \).

**Projections under 90, 180, and 360 days of NPIs**

Projections of the NPIs durations of 90, 180, and 360 days were made for the top 15 economies. We assume that when the NPIs are not imposed, the virus will spread in a natural manner, characterized by the basic reproduction number at that moment. The basic reproduction number is assumed to remain constant after that time as no further NPI measures are imposed. The resulting model after the termination of NPIs, essentially reduces to the regular SEIR model, as shown in Eq. (11).

\[
\begin{align*}
\frac{dS}{dt} &= \begin{cases} 
-a_0 \exp(-\lambda t) IS/N & t < \tau \\
-\beta(\tau) IS/N & t \geq \tau
\end{cases} \\
\frac{dE}{dt} &= \begin{cases} 
-a_0 \exp(-\lambda t) IS/N - \alpha E & t < \tau \\
\beta(\tau) IS/N - \alpha E & t \geq \tau
\end{cases} \\
\frac{dI}{dt} &= \alpha E - \gamma I \\
\frac{dR}{dt} &= \gamma I
\end{align*}
\quad (11)
\]

where \( \tau \) is the NPI duration, and \( \beta(\tau) \) is given in Eq. (4). Eq. (11) determines the transition rates among the four states considering the NPIs duration length \( \tau \). Another piece of crucial
information is the initial value of the numbers of people of the four states. Here we set the initial numbers of $I$ and $E$ as the average numbers of the two states from $t = 0$ to $\tau$.

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Data availability

Data necessary to reproduce all the results of this study are documented in the main text, the extended data and supplementary tables.

Code availability

Code necessary to reproduce all results of this study is available upon publication (and for review)

Author contributions

JH and XG contributed equally to the conceptualization, data analysis, results interpretation, codes development, and manuscript writing. XD contributed to data collection and codes development. TS contributed to data collection and data analysis. JL contributed to results interpretation.

Competing interests

The authors declare no competing interests.

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Supplementary Text

Data source of COVID-19 cases

The data source of inflected, susceptible recovered, and deaths in China is National Health Commission (NHC). The data source outside China are the World Health Organization (https://www.who.int/emergencies/diseases/novel-coronavirus-2019) and John Hopkins University & Medicine, Coronavirus Resource Center (https://coronavirus.jhu.edu/map.html). The above data are also collected and centralized by Tencent Inc., through the webpage:

https://news.qq.com/zt2020/page/feiyan.htm#/global

Information of non-pharmaceutical interventions

The information of non-pharmaceutical interventions including time, measures and stringency implemented in the top 15 economies was collated from the following websites:

[1]http://www.gov.cn/xinwen/2020-01/23/content_5471751.htm
[2]http://www.gov.cn/xinwen/2020-05/17/content_5512295.htm
[3]https://www.usatoday.com/story/news/world/2020/03/17/coronavirus-how-countries-across-globe-responding-covid-19/5065867002/
[4]http://m.xinhuanet.com/2020-03/10/c_1125687804.htm
[5]http://www.xinhuanet.com/world/2020-03/18/c_1125730281.htm
[6]http://www.xinhuanet.com/2020-03/23/c_1125754382.htm
[7]http://news.cctv.com/2020/05/12/ARTI8Uk4IG6kmvh8akocBe01200512.shtml
[8]http://www.xinhuanet.com/politics/2020-03/15/c_1125713670.htm
[9]http://www.chinanews.com/gj/2020/03-24/9135832.shtml
[10]https://www.smh.com.au/national/nsw/nsw-records-seven-new-coronavirus-cases-
aims-to-carry-out-8000-tests-per-day-20200424-p54mt6.html

[11]http://m.haiwainet.cn/mip/3541093/2020/0326/content_31752416_1.html

[12]http://news.cctv.com/2020/03/21/ARTIg9eEhi3Xrrmbwy1AbXD8200321.shtml

[13]https://n.eastday.com/pnews/1589774282015417

[14]http://k.sina.com.cn/article_6212976462_172527f4e00100s2k2.html

[15]http://news.cctv.com/2020/03/26/ARTI3l9nWl8JgeEDa5RErD200326.shtml

[16]https://www.gov.uk/coronavirus

[17]https://www.fmprc.gov.cn/ce/cemx/chn/sgxx/t1764910.htm

[18]https://www.dahebao.cn/dahe/appweb/1515122?cid=1515122

[19]https://baijiahao.baidu.com/s?id=1666811800411745620&wfr=spider&for=pc

[20]https://population.un.org/wpp/Download/Standard/Population/

[21]https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports