Cost-effectiveness Analysis of Antiepidemic Policies and Global Situation Assessment of COVID-19

Authors: Liyan Xu[1]*, Hongmou Zhang[2]*, Yuqiao Deng[1], Keli Wang[3], Fu Li[1], Qing Lu[4], Jie Yin[5], Qian Di[6], Tao Liu[4], Hang Yin[1], Zijiao Zhang[1], Qingyang Du[1], Hongbin Yu[1], Aihan Liu[1], Liu Liu[7], Yu Liu[3]†

Affiliations:

[1]College of Architecture and Landscape Architecture, Peking University, Beijing 100871, China.

[2]Future Urban Mobility IRG, Singapore–MIT Alliance for Research and Technology, Singapore 138602.

[3]School of Earth and Space Sciences, Peking University, Beijing, 100871, China.

[4]College of Urban and Environmental Sciences, Peking University, Beijing 100871, China.

[5]Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA 02115, USA.

[6]Research Center for Public Health, School of Medicine, Tsinghua University, Beijing 100084, China

[7]CitoryTech, Shanghai 200063, China.

*These authors contributed equally to this work.

†Corresponding author. Email: liuyu@urban.pku.edu.cn.

Abstract: With a two-layer contact-dispersion model and data in China, we analyze the cost-effectiveness of three types of antiepidemic measures for COVID-19: regular epidemiological control, local social interaction control, and intercity travel restriction. We find that: 1) intercity travel restriction has minimal or even negative effect compared to the other two at the national level; 2) the time of reaching turning point is independent of the current number of cases, and only related to the enforcement stringency of epidemiological control and social interaction control measures; 3) strong enforcement at the early stage is the only opportunity to maximize both antiepidemic effectiveness and cost-effectiveness; 4) mediocre stringency of social interaction measures is the worst choice. Subsequently, we cluster countries/regions into four groups based on their control measures and provide situation assessment and policy suggestions for each group.

Coronavirus disease 2019 (COVID-19) has been recognized as a pandemic by the World Health Organization in March 2020 (*1*). Nonetheless, on March 18, mainland China observed their first day with zero increase of local cases since the outbreak (*2*). This indicates that, aside from the imported cases, the pandemic has been locally close to the end. Many experiences and lessons can be shared by the rest of the world from the trajectories of the outbreak and the control strategies in mainland China. One question that is of particular importance is the cost-effectiveness of different antiepidemic measures. Drawn from the Chinese experiences and lessons, three categories of measures have been implemented: a) "regular" epidemiological control and prevention measures, including identification of infected cases, tracing their close contacts, and quarantines for both; b) *In-city* activity restrictions, including work-from-home, shut-down of schools and public spaces, cancellation of events, and lock-down of residential neighborhoods; c) *Inter-city* travel restrictions, including temperature screening at all transportation terminals, cancellation of flights and trains, and eventually travel bans from/to certain cities. Specifically, (b) and (c) are considered "irregular," which contain the spread of disease in an aggressive manner *through the suppression of all possible social interactions*. However, these measures lead to enormous economic loss, which may mean higher unemployment rates, and shortage of food, medical services, and other necessities. Those chain effects may also endanger the lives of certain social groups. Fundamentally this is a trolley dilemma, and the life and health of human beings can hardly be evaluated using monetary values. Nevertheless, a comprehensive understanding of the cost of each measure—including the opportunity cost of the shut-down economic activities—and the effectiveness of lifesaving can still help policy makers to compare different antiepidemic strategies in a more operable way. Further, with these insights, we can then perform a cross-sectional assessment of the situation of the global antiepidemic campaign regarding the aforementioned measures in different countries/regions, such that typical policies can be clustered and prescriptive policy suggestions can be provided accordingly.

In prior research, scholars have used deductive models to find that the *timing* of lock-down, including both intercity travel restrictions and social distancing, significantly changes the size of infected population and the spatial extent of spread (*3–6*). Nonetheless, all prior research only focused on specific instances of policies without discussing generalizable impacts of different measures and lacked a cost-effectiveness assessment of each measure (*7–9*). In this article, based on the transmission pattern of COVID-19 in China, we build a two-layer contact-spread model (Fig. 1) to recover the whole spatio-temporal transmission process, especially the early-stage numbers and distribution of cases at the prefecture level (see Supplementary Text). With this model as a generalizable baseline, we conducted a comprehensive sensitivity analysis for all antiepidemic measures (Fig. 2) and concluded the following assessment on the *effectiveness* of the measures, in terms of number of infected cases, and number of infected cities.

1. Containing daily social interaction, parameterized in the model as κ_I, κ_E for the infected and the exposed populations, is *the most effective measure* for controlling both the number of infected cases and the spatial extent of the spread. More specifically, we find that a) the controls of κ_I and κ_E show comparable and substitutable effects in containing the spread of disease, with different elasticity in different stages of the epidemic. Controlling κ_E is more effective when the number of cases is small (e.g., fewer than 10 in a city), and κ_I is more effective when the number of cases is sufficiently large. The implication is that at the early stage of transmission, comprehensive epidemic surveys and contact tracing, alongside with strict

quarantine and social distancing, should be used to prioritize the reduction of the social interaction levels of the exposed population (κ_E), while after the number of cases has increased to a sufficiently high level, comprehensive testing and identification of all infected cases should be prioritized in order to reduce the social interaction levels of the infected population (κ_I). b) Stricter control of social interaction for both κ_I and κ_E have *diminishing returns in reducing the number of cases, but increasing returns in limiting the spatial extent of spread*. For example, in one month of simulation, when daily social interaction drops from 100% to 90% of the normal level, the number of infected cases drops by 10%–25% (depending on the stage of epidemic), while the number of cities with infected cases drops only by 0–1%; when daily social interaction drops from 10% to 0, however, the number of cases drops only by 0.05%–0.5% for infected cases versus 2%–35% for cities with infected cases. An exception is at the ending stage of the epidemic, when controlling social interaction has increasing returns in both effects. c) The effects of the epidemiological and social interaction control measures are *monotonic* for the reduction of infected cases and the spatial extent of spread: the stricter they are enforced, the lower number of infected cases and the narrower spatial extent of spread can be observed.

2. The time of reaching turning point is *independent* of the current number of infected cases but is only related to the stringency of epidemiological and social interaction control measures, i.e., the relative change of κ_I, κ_E. When the two parameters are 1/4–1/3 of the normal everyday values, the turning point comes in two weeks and the clearance of cases happens in two to three months; when κ_I, κ_E are larger than 1/2–2/3 of the normal values, the turning point will never come, i.e., the peak value of case numbers will remain the same as if there are no such measures, but they only delay the time of peak.

3. Except at the early stage and the ending stage, intercity travel restriction has only minimal effect on both the reduction of infected cases and control of disease spread in a city network. Overall, compared with in-city epidemiological and social interaction control measures, the contribution of intercity travel restrictions to the reduction of the number of infected cases and the spatial spread of disease is much smaller—lower by two orders of magnitudes. When the number of cases is sufficiently large, intercity travel restriction even exacerbates the situation since it limits the social interaction of infected cases, and "condenses" R_0 locally (*10*). Therefore, to national or regional governments who manage a city network, and to international antiepidemic collaboration, travel restriction should only be regarded as an auxiliary measure at the beginning and ending stage of the spread to protect cities which have not been infected at all, or only with a sufficiently small number of cases. In the latter case epidemiological and social interaction control measures should also be implemented simultaneously to get the health care system and other prevention measures prepared.

The simulation-based formal analysis in points (1) to (3) is consistent with the empirical evidence in China. The lockdown of Wuhan, and nationwide strict enforcement of epidemiological control and social distancing policies around January 23, including the cancellation of all Chinese New Near gatherings mark the key move of the antiepidemic campaign. At that time point, all other cities in China were at early stages of the epidemic, which guaranteed the effectiveness of the Wuhan travel ban. In addition, with aggressive social interaction control in all cities the turning point of the number of cases arrived in two weeks outside of Wuhan. In Wuhan, the key move was the functioning of 16 *fāngcāng* hospitals (mobile cabin hospitals) in early February which enabled citywide comprehensive quarantine of the infected population (*11*). This measure reduced the social interaction of infected cases to almost *zero*, and together with strict social distancing they effectively reversed the trend of spread after two weeks. In terms of intercity travel restrictions, since they were during the Chinese New Year and the extended holidays, and overlapped with social distancing measures, the net effect could not be easily isolated empirically. Nonetheless, since mid-February the economy had re-opened. By the end of March, the intercity migration in southern and eastern Chinese cities had recovered to the same level as in previous years (*12*), but most cities still observed almost zero increase of infected cases. This further supports that the effectiveness of travel restriction is very limited for the cities with small numbers of cases. Another evidence to support this point is the 300,000 people who left Wuhan right before the lockdown night (*13*). This "escaped" population did not significantly change the effectiveness of the national antiepidemic effort.

Further analysis on the cost-effectiveness of the measures shows more irregularity and non-linearity, leading to more nuanced relationships (detailed in the Supplementary Text). Here we summarize the most critical general patterns as follows:

1. The measures which can achieve both high antiepidemic effectiveness (low number of cases and narrow spatial spread) and high cost-effectiveness (smaller loss of economic outputs) only exist at the early stage of transmission. At the early stage, if epidemiological and social interaction control measures can be strictly enforced (sufficiently low κ_I and κ_E), it is possible to keep the spread at a low level, with a loss of economic outputs only up to 4%. The intuition is as follows: based on the assumptions of this article, the early-stage measures only include comprehensive testing, close contact tracing, and quarantine, but do not include indiscriminate restrictions of in-city social interaction and intercity travel, which incurs high costs. The policy implication is straightforward: for early-stage cities and regions, it is critical to practice epidemiological control interventions, but not to necessarily mobilize the whole society into social interaction reduction. This finding is consistent with the suggestions in *(5)*.

2. Except for the early stage, it is *impossible to simultaneously achieve both high antiepidemic effectiveness and high cost-effectiveness*. Except for a few "plateaus," the effectiveness of epidemiological and social interaction control measures monotonically increases with the stringency of control measures. However, the cost and cost-effectiveness functions are non-monotonic and there usually exists more than one peak (see details in the Supplementary Text), which in most cases do not coincide with the effectiveness peak. Typically, the costs are the lowest when the control measures are at sufficiently low or sufficiently high levels. While the latter case has been explained in the last point, the sufficiently low control measure scenario basically leaves the whole population to be infected.

Therefore, the tradeoff between sufficiently low and sufficiently high levels of control measures depend on many technological factors, including the short-term and long-term capacity of healthcare systems, long-term uncertainty of virus mutation, and development of vaccines, as well as many non-technological factors, including the risk averse attitudes for the short term and the long term, the mental discounting between short-term and long-term tradeoffs, and the fundamental value judgement on the "value of lives," the discussion of which are beyond the scope of this article, and will be left for discussion at the end of this article.

3. Lastly, although it is difficult to choose the optimal control strategy, the worst choice is explicit: *mediocre control of social interaction*, e.g., social distancing with leakage. This choice still incurs 20–60% loss of economic outputs, but only achieves 30–40% reduction in the number of cases, an extent which is insufficient to overturn the epidemic curve. Except for moderately delaying the spread of disease which may be taken advantage of to get the healthcare

system prepared, this strategy is the worst choice in all other dimensions.

With the formal results above, we can now perform a cross-sectional assessment of the global situation of the antiepidemic campaign from a transmission-prevention policy perspective. Among the three types of measures (epidemiological control measures, social distancing, and travel restriction), we disregard the travel restriction measure as our results clearly show that it is ineffective for most countries/regions under the current situation (we will discuss the exceptions later). Rather, we use two datasets (*14*, *15*) which codified the antiepidemic measures chosen by countries/regions as of April 7 (due to the lack of testing data, we use Wuhan as a proxy for mainland China), and for the countries/regions analyze the relationship of their two stringency indices, κ_i and κ_e, i.e., the activity levels of the infected and exposed populations, and the respective effectiveness on the reduction of infected cases. Based on the stringency of the two dimensions of antiepidemic measures, we can divide all countries/regions into three groups (Fig. 3), each with a different antiepidemic "strategy": *elimination*, *control*, and *delay*. More than 100 countries/regions are not included because of the lack of data. We will also discuss the implications of this fact.

1. The "elimination" group: This group (up right corner of Fig. 3) consists of only a few countries/regions, including mainland China (represented by Wuhan), Hong Kong SAR, Vietnam, UAE, Bahrain, etc., all with $R_0 \ll 1$, such that the epidemic could be expected to dwarf within a reasonably short time period. Mainland China is the most prominent example of this group, where aggressive measures have been taken on both dimensions to reduce the activity of the infected population as well as the exposed population. The measures include effective epidemiological control interventions, such as comprehensive testing and close contact tracing, and also aggressive social distancing measures, such as shutdown of schools, workplaces, and public transport, cancellation of events, and mass disease control education. These measures incur 40%–90% loss of economic outcome in a month, and the loss accumulates as the epidemic is not completely "eliminated". Obviously, the underlying value judgment of the elimination strategy is an overwhelmingly high weight on health and lives over any cost-control or cost-effectiveness reckoning.

Although the treasuring for lives is always respectable, long-lasting economic tightening also constitutes a threat to society, especially to the disadvantaged social groups. Due to the existence of asymptomatic carriers, false-negative test results, and international imports of cases, a complete elimination of the epidemic is extremely difficult. Thus, if the aim is to literally eliminate all cases, the economic losses are highly likely to accumulate to an unbearable level. Therefore, we suggest that countries/regions which have followed the elimination strategy consider turning to the "control" strategy (elaborated below) to avoid excess economic losses on the condition that the active number of infected cases has been reduced to a sufficiently low level. We also suggest that these countries/regions keep the travel restriction measures—the most effective measure at this stage of the epidemic indicated by our simulation results.

2. The "control" group: This group includes South Korea, Singapore, Qatar, Norway, Slovenia, Russia, and New Zealand, etc., all with $R_0 < 1$, but still not sufficiently small, such that the epidemic can be reduced to a lower level (but not eliminated), depending on the stringency of intervention measures. The Singapore in February was the most prominent example within this group, where antiepidemic measures have been mild enough not to affect everyday life by aggressive social distancing. Through regular epidemiological control practices, they were managed to maintain a daily increase of infected cases fewer than 10, and only suffered 0.5%–4% loss of economic outcome in a month. The control strategy requires a highly

capable epidemic control system. Given the aforementioned long-term uncertainties, even with such a capable system, the strategy is still a tightrope-walking game with the risk of abrupt system overload by accidentally untracked surges of infection, which, unfortunately, appears to be the case in Singapore in early April. Under such circumstances, a timely turn to the "elimination" strategy may be necessary.

3. The "delay" group: All other countries/regions in Fig. 3 belong to the third group, which appears to follow the "delay" strategy, with $R_0 > 1$, such that the epidemic will continue to grow. This is often referred to as the "flatten the curve" strategy, which aims not to reduce the epidemic to an as-low-as-possible level within a short period of time, but only to delay its growth through mediocre epidemiological control and social distancing measures. Our results show that this is usually the worst scenario in terms of cost-effectiveness. A country/region may opt to this strategy because their tradeoff between short-term certainty (economic loss avoidance) and long-term uncertainty (possible disappearance of the epidemic in the summer, development of vaccines, etc.) leans towards the former. Unless they have strong evidence to justify the tradeoff, we strongly suggest they reconsider. Moreover, our results show possible directions to improve—enhancing the social interaction control for the infected population through more comprehensive testing or enhancing the social interaction for the exposed population through stricter social distancing measures, whichever sees fit based on the location of the country/region on Fig. 3.

4. Rest of the world: More than 100 countries/regions do not appear in Fig. 3 due to the lack of data, most of which are third-world countries/regions. Although little information is available to us about the situations in these places, we conjecture that they may at this moment be pursuing cost-effectiveness of their antiepidemic interventions because of their limited availability of resources, which we call the "worth every penny" strategy. As our results show that the most cost-effective measures are usually neither the most effective one (actually they are usually very *ineffective*), nor the least costive ones, the "worth every penny" strategy is not a good option either. If a country/region opts to this scenario solely because of the lack of resources, it should be viewed as a humanitarian disaster, and we call for international aid in this situation.

At the end, we acknowledge the extreme difficulty of even trying to lay out the comparison between human lives and economic activities, or the tradeoffs of lives between different social groups. We believe that the ethical discussion should be open to the whole society and hope that this article can contribute to the discussion.

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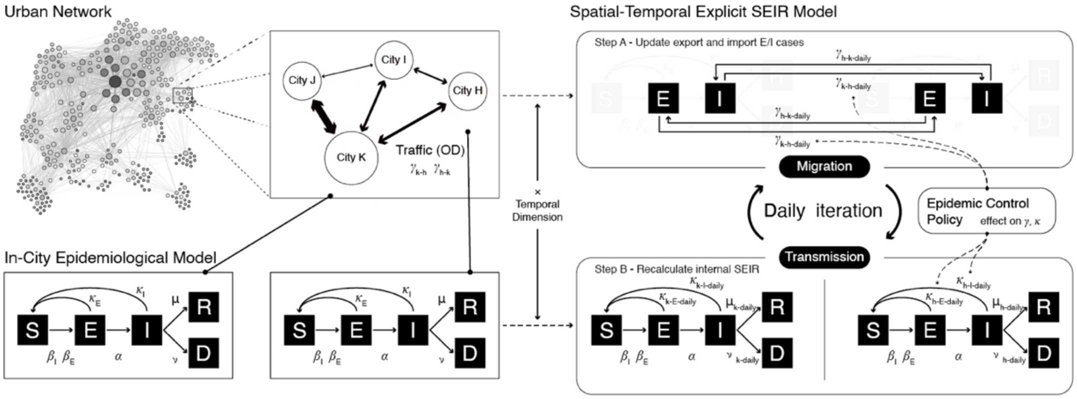

Fig. 1. Structure diagram of the contact-dispersion model. The model is consisted of an in-city layer of SEIR model (*16*) and a network transmission layer based on intercity migration. Through intercity travel, the numbers of exposed and infected populations are adjusted daily. The model is calibrated using the migration data and the number of reported cases in China. See Materials and Methods for model specifications.

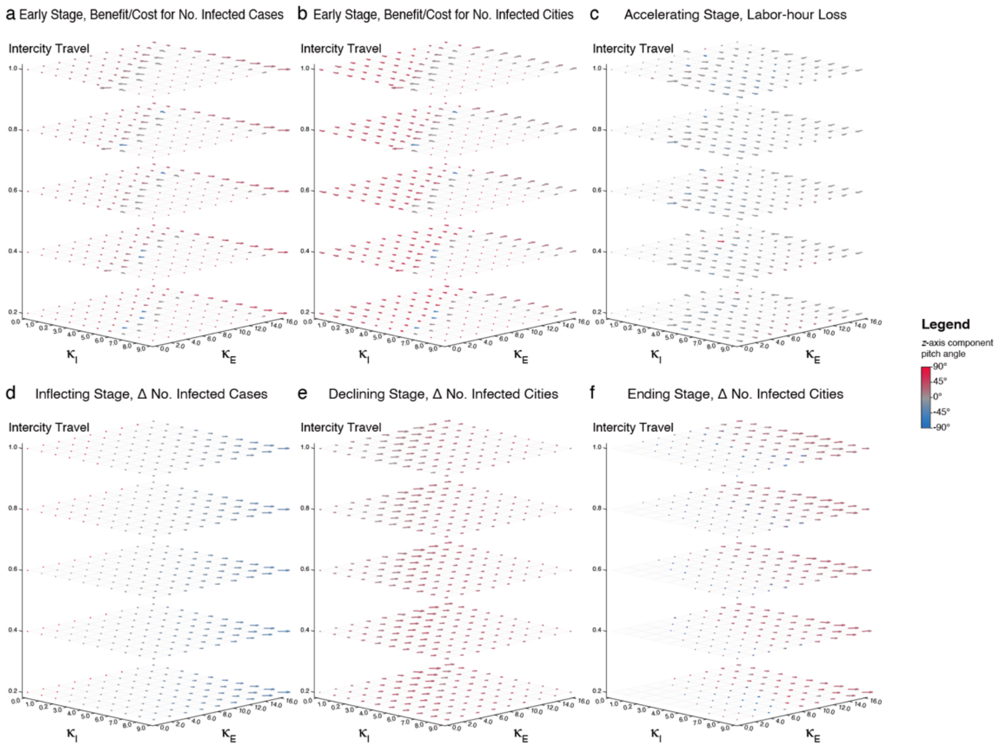

Fig. 2. Gradients of spread of disease indicators with social interaction control measures (κ_I, κ_E) and intercity travel intensity at different stages of the epidemic. (**a**) Gradient of effectiveness-cost ratio with regard to the number of infected cases at the early stage. (**b**) Gradient of effectiveness-cost ratio with regard to the number of infected cities at the early stage. (**c**) Gradient of labor-loss hour at the accelerating stage. (**d**) Gradient of change of the number of infected cities at the inflecting stage. (**e**) Gradient of change of the number of infected cities at the declining stage. (**f**) Gradient of change of the number of infected cities at the ending stage. See definition of different stages and the calculation of gradient in Materials and Methods.

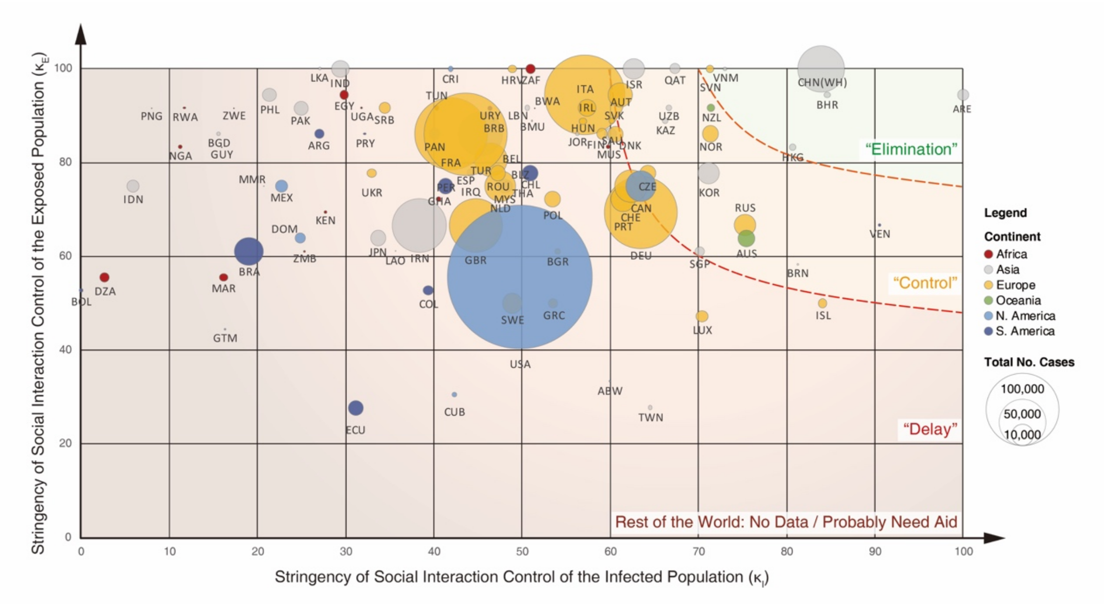

Fig. 3. Groups of antiepidemic policy based on stringency of social interaction measures. Each dot represents a country/region. The sizes of the dots indicate the number of infected cases on April 7, 2020.