Impacts of Early Interventions on the Age-Specific Incidence of COVID-19 in New York, Los Angeles, Daegu and Nairobi

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Abstract:

COVID-19 has caused an unprecedented public health crisis and economic shock to the global economy. While many countries were affected, regions with an older population and weaker public health interventions tended to suffer more morbidity and mortality. We developed an open-source/open data age-specific and multiple-stage susceptible-exposed-infected-recovered-hospitalized-quarantined-dead (SEIR-HQD) model Utilizing the latest estimates of epidemiological parameters and demographic data, we model the potential effects of various interventions in four representative cities with different population structures - New York, Los Angeles, Daegu and Nairobi. Our modeling quantifies the value of early interventions, which avoided an additional 5%, 16%, 37% and 43% of the infections in Daegu, Nairobi, New York and Los Angeles, respectively, compared to what has been observed in the four cities. Critically, we find that school closures, working from home, and reduction in other mobility were most beneficial for younger population (0-19 years old), middle-age (20-59 years old) population and older population (60 years and older), respectively across each city. Specifically, school closure avoided 25%, 18%, 16% and 12% of the infections for the population under 20 years old in Daegu, Los Angeles, New York and Nairobi, respectively. A 50% and 80% population working from home policy avoids 8% and 15% of the infections. Reduction in mobility was more effective than the working from home strategy. Any single social distancing policy if enacted alone can delay the spread of COVID-19 but was unable to totally suppress the infection. Coordinated policy action can be highly effective. Increasing the quarantine rate to 10% of infectious cases was more effective than strict social distancing alone in this study, although together they can suppress 80% of the epidemic. A combination of moderate social distancing and quarantine strategies was able to avoid 99% of the infections.

Introduction

The outbreak of COVID-19 triggered heterogenous responses from countries across the world. While the effectiveness of these containment strategies is still emerging, and critical lessons for how long social isolation and testing must remain in place, as well as the need to guard against re-infection demand immediate access to models that can be ground-truthed by comparing model results and the emerging responses to policies already in place in diverse urban settings. For the most hard-hit countries, such as the US, Italy and Spain, there are greater percentages of older population who are facing much higher risks of hospitalization and fatality due to changes of immune system and the impact of preexisting health conditions over time.[1] Studies have found that COVID-19 was an emergent disease of ageing.[2]

The effects of population ageing on the outcomes of COVID-19 require much more resources in healthcare services and facilities, which is places a significant burden on the health care infrastructure of many ageing countries. Therefore, countries with high proportion of older population should prioritize strategies that effectively protect older people during the epidemic. The difference in demographic characteristics may call for targeted interventions to suppress the spread of COVID-19. Studies have emphasized the importance of incorporating the demographic information in curbing the spread of the epidemic.[3] An important recent study by the Imperial College COVID-19 Response Team explored the impacts of public health interventions in 11 European countries.[4] Here we focus on individual cities where the policy steps are more homogeneous and can be well-described in the model we present and make available here. Understanding the effects of population ageing on the spread of the epidemic under various containment interventions enables policymakers to make effective decision making to avoid massive hit of the novel coronavirus and relief the pressure on healthcare systems.

Important and critically needed modeling studies have explored the effects of different interventions, such as social distancing, school closing and managing dynamics of population movement.[5–9] Social distancing has been recognized as one of the most effective mitigation strategies.[10,11] An under-studied issue is that of mental health impacts of these strategies across different segments of the population. In addition to social distancing, there are additional opportunities for countries to make transition from stopping the economy. Strategies to get young people back to work and protect older population and epidemiological surveys to track the exposed cases and strict quarantine are implemented well in Korea and Singapore. Strategies tailored to different age groups within the population are in an urgent need to recover the economy.

In this study, we focused on four cities, New York, Los Angeles, Daegu and Nairobi, that both shared similarities and reflected diversities in terms of demographics and containment strategies. As the world's most impacted nation, the number of COVID-19 cases in the United States (US) surged to over half a million by mid-April.[12] New York, the most populous US metropolitan area, was hit the hardest. By contrast, Los Angeles, had a total number of infected cases accounting for fewer than 10% of that in New York. Many factors influence such differences, but the timeline of policy interventions in Los Angeles and New York indicates that New York took actions even faster since the detection of the first case. However, the intervention policy is less detailed and instructive for the public to follow than the one in Los Angeles. Explanations for the rapid increase in the spread of COVID-19 have been proposed.[13,14] Compared with the containment strategy in the US overall, Korea implemented a faster and effective testing regime, contact-tracing, and quarantining of people. Detailed online education and clarification of requirements for isolation where widely disseminated online. In total the South Korean policies greatly increased the quarantine rate of exposed population. Nairobi, as the capital city of Kenya, has a relatively younger population than the other three cities. Kenya also take a fast response since the first case was detected. Four cities all ordered people to keep social distancing, close schools and hand hygiene. While Korea and Kenya called people to wear face masks in the beginning, the US did not encourage people to wear face masks/cloth face covering until April 3, 2020.[15] The difference in the interaction of these non-pharmaceutical interventions and age structures of population might deviate the spread of COVID-19.

Methods

In this study, we expanded a SEIR model to an age-specific SEIR-HQD model for a period of 365 days. SEIR-HQD model considers 7 states of infection including susceptible (S), exposed (E), infectious (I) and recovered (R), hospitalized (H), quarantined (Q) and dead (D). The SEIR-HQD model incorporates the age structure, birth rates and death rates dynamics of the affected population in Daegu, New York, Los Angeles and Nairobi.

We stratified each population into 9 age groups by a 10-year band, with the last age group set as those 80 years and older. We assume the population in these four cities are closed systems without population flow inside or outside the cities. When the susceptible populations are exposed to infectious individuals, a percentage then transition into infected status at a given probability defined by an age-specific transmission rate. After the incubation period, the exposed population then become infectious, but if they are quarantined, we assume that they do not impact susceptible individuals in the next generation. For those who are infectious, given the hospitalization rate of infectious cases, we further calculate the number of people who are in need of further medical care in the hospital. Our model also simulates the quarantine of individuals and hospitalized cases are sub-states of infected cases that will not cause a secondary infection. The quarantine individuals might also become hospitalized. The epidemic evolution model is described as follows:

$$\frac{dS_{i,t}}{dt} = \frac{\nu}{n}\sum_{i=1}^{n} pop_i - \beta_{i,t}\frac{I_{i,t} - H_{i,t} - Q_{i,t}}{pop_i}S_{i,t} - \mu_i S_{i,t}$$

$$\frac{dE_{i,t}}{dt} = \beta_{i,t}\frac{I_{i,t} - H_{i,t} - Q_{i,t}}{pop_i}S_{i,t} - \sigma E_{i,t} - \mu_i E_{i,t}$$

$$\frac{dI_{i,t}}{dt} = \sigma E_{i,t} - \gamma_i I_{i,t} - \mu_i I_{i,t} - \omega_i I_{i,t}$$

$$\frac{dH_i}{dt} = \varphi_{i,t}\left(I_{i,t} - H_{i,t}\right) - \omega_i H_{i,t} - \gamma_i H_{i,t} - \mu_i H_{i,t}$$

$$\frac{dD_{i,t}}{dt} = \omega_i I_{i,t}$$

$$\frac{dQ_{i,t}}{dt} = \rho\left(I_{i,t} - Q_{i,t} - H_{i,t}\right) - \varphi_i Q_{i,t} - \gamma_i Q_{i,t} - \omega_i Q_{i,t} - \mu_i Q_{i,t}$$

$$\frac{dR_{i,t}}{dt} = \gamma_{i,t} I_{i,t} - \mu_i R_{i,t}$$

$S_{i,t}$ is the susceptible population in age group i on day t,
ν is the birth rate per thousand population,
μ_i is the death rate of population in age group i,
n is the number of age groups, pop_i is the number of population in age group i,
$\beta_{i,t}$ is transmission rate, defined as the probability of infection between a susceptible and infected individual,
$I_{i,t}$ is the infected people in age group i,
$E_{i,t}$ is the exposed population in age group i,
σ is the daily probability of an exposed individual becoming infectious, which equals to $1 - \exp\left(-\frac{1}{\mathrm{d}_{inc}}\right)$, where d_{inc} refers to duration of average incubation time,
ρ is quarantine proportion of exposed individuals,
$\gamma_{i,t}$ is the probability of an infected individual that recovers during the infectious duration d_{inf}, so that $\gamma_{i,t} = 1 - \exp\left(-\frac{1}{\mathrm{d}_{inf}}\right)$,
$\varphi_{i,t}$ is the hospitalization rate in age group i,
$\Omega_{i,t}$ is the fatality rate of infected individuals,
$Q_{i,t}$ is the number of individuals that are quarantined,
$R_{i,t}$ is the number of infected individuals who recover.
The parameters involved in the model are obtained from literature and are presented in Table 1.

Parameters	**Value**	**Reference**
Basic reproduction number R_0	2.92 (2.28, 3.67)	Liu et al. (2020)[16]
Transmission rate	Varies by age, see Appendix 1.	Estimated in this study
Average incubation period, $\mathbf{d}_{inc}$	6.4 days	Backer et al. (2020)[17]
Average duration of infection, $\mathbf{d}_{inf}$	7-11 days (assume growing by age)	Cao et al. (2020)[18] and Bi et al. (2020)[19]
Initial number of infected, $\mathbf{I}_0$	200 or 500 per million	Abbott et al. (2020)[20] and Prem et al. (2020)[9]
Hospitalization rate, $\boldsymbol{\varphi}_{i,t}$	Varies by age, see Appendix 1	Ferguson et al. (2020)[7] and Verity et al. (2020)[1]
Quarantine rate, $\boldsymbol{\theta}$	0%-80%	Assumed in scenarios
Fatality rate, $\boldsymbol{\omega}_{i,t}$	Varies by age, see Appendix 1.	Verity et al. (2020)[1]

Table 1 Parameters in the age-specific SEIR-HQD model

The transmission rate differs from the location, population mobility and contact probability. Therefore, we calculate the transmission rate matrix based on contact matrices in different location settings at country level.

We first adjusted the contact matrices by age-specific population, the more population in certain age group, the higher probability of this group population gets in contact with one in other age groups. Then we estimate the transmissibility using method:[21]

$$\mathbf{C}_{i,j}^{pop} = \mathbf{C}_{i,j} \times \boldsymbol{prop}_i^{pop} / \boldsymbol{prop}_j^{pop}$$

$$\det\left(\mathbf{C}_{i,j}^{pop} - \lambda \boldsymbol{I}\right) = 0$$

$$\tau_i = \frac{R_0}{max(\lambda) \times \mathrm{d}_{inf}{}^{T}}$$

$$\boldsymbol{\beta} = \tau_i \times \mathbf{C}^{\boldsymbol{pop}}$$

where i and j represent age groups, $\mathbf{C}^{pop}$ is contact matrix in each city, $\boldsymbol{prop}_i^{pop}$ is the proportion of population in age group i to the total population in a city, τ_i is the transmission probability of a contact between an infectious individual with a susceptible one, R_0 is the basic reproduction rate, and $\boldsymbol{\beta}$ is the transmission rate matrix among individuals in different age groups.

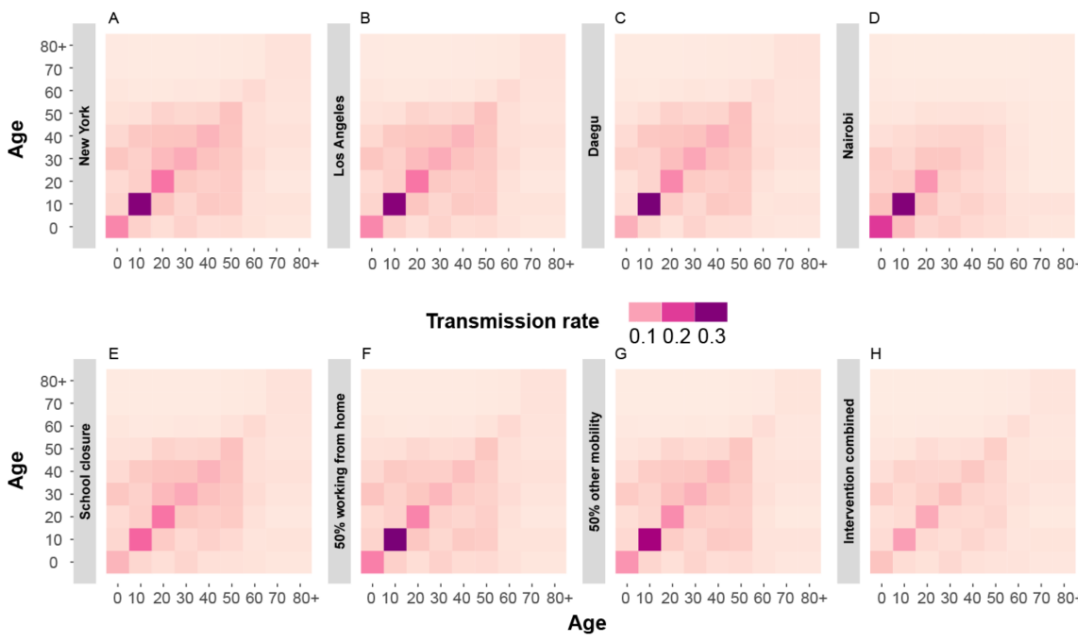

Figure 1 Transmission rate matrices in different cities (Figure 1A-1D) and different counterfactual transmission rate matrices in different intervention scenarios (Figure 1E-1H)

In addition to factors such as population density and social habits, the population age structure also influences transmission rates among different age group population. Nairobi has a younger population than the other three cities, thus there are lower transmission rates among older people and higher transmission rate among the younger people than that in the relatively ageing cities in the US and South Korea (Figure 1). The population age structure information is listed in the Appendix 1.

The timeline of the policy interventions illustrated the speed of reaction to suppress the epidemic peaks in each city (Figure 6). Since Nairobi was hit later than other three cities, we can forecast the effects of implemented policy interventions, and outcomes, may evolve significantly from what we have modeled here.

1. Scenario design for interventions and the timing of policy action

Applying the SEIR-HQD model, we designed two sets of scenarios to explore: 1) the age-specific effects of policy interventions and 2) the effectiveness of policy action at different time points since the diagnosis of the first case.

For the age-specific effects, we designed 7 scenarios that tested school distancing, reduction in other mobility, increasing quarantine rates and a mixture policy package.

Policy action / Scenario	School closure	Working from home	Reduction in other mobility	Quarantine rate
Scenario A	100%	0%	0%	0%
Scenario B	0%	50%	0%	0%
Scenario C	0%	80%	0%	0%
Scenario D	0%	0%	50%	0%
Scenario E	0%	0%	80%	0%
Scenario F	0%	0%	0%	10%
Scenario G	100%	50%	50%	10%

Table 2 Scenario design for age-specific effects analysis.

We also reviewed the policy actions in four cities from the first case detected to April 9, 2020 (Figure 2). We followed the real policy actions to simulate the business-as-usual scenarios in the four cities. Then we move each strategy 1 week earlier to see the effects of early actions.

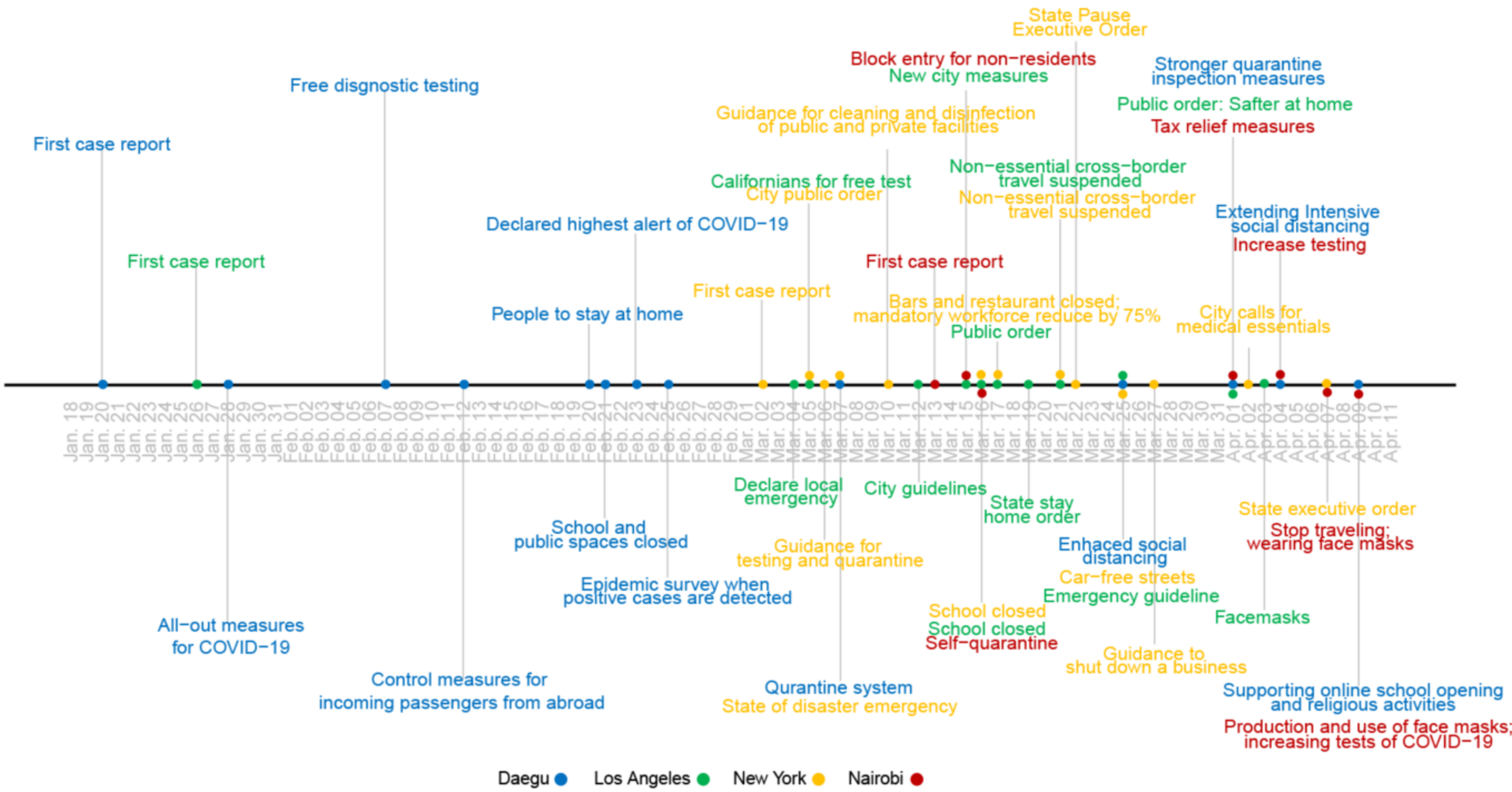

Figure 2 Timeline of policy interventions and first case reports in four cities, Daegu, South Korea, Los Angeles, USA, New York, USA and Nairobi, Kenya. Detailed information on the interventions summarized here is provided in Appendix 1.

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Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

1. The age-specific effects of different interventions on the outcomes of COVID-19

Figure 3 presents the temporal evolution of the number of individuals in each wellness/illness category ("status") over a year period in the four cities simulated per million residents of initial susceptible population with no intervention. It shows that the COVID-19 outbreak hits the four cities dramatically although differently, mainly due to the variation of population age structures. In the 'no intervention' scenario, COVID-19 causes 550,000 infected cases per million population in Nairobi, which is 35% higher than the reported infected cases in New York, Los Angeles, Daegu. This was mainly due to the higher contact rates among younger population was relative to the older population, which caused higher transmission rates among them. However, the deaths related to COVID-19 were much lower than other three cities with older populations. As seen in Figure 3, for each million of the susceptible population, COVID-19 caused 29% more deaths in Daegu than in Nairobi, largely due to the older demographics.

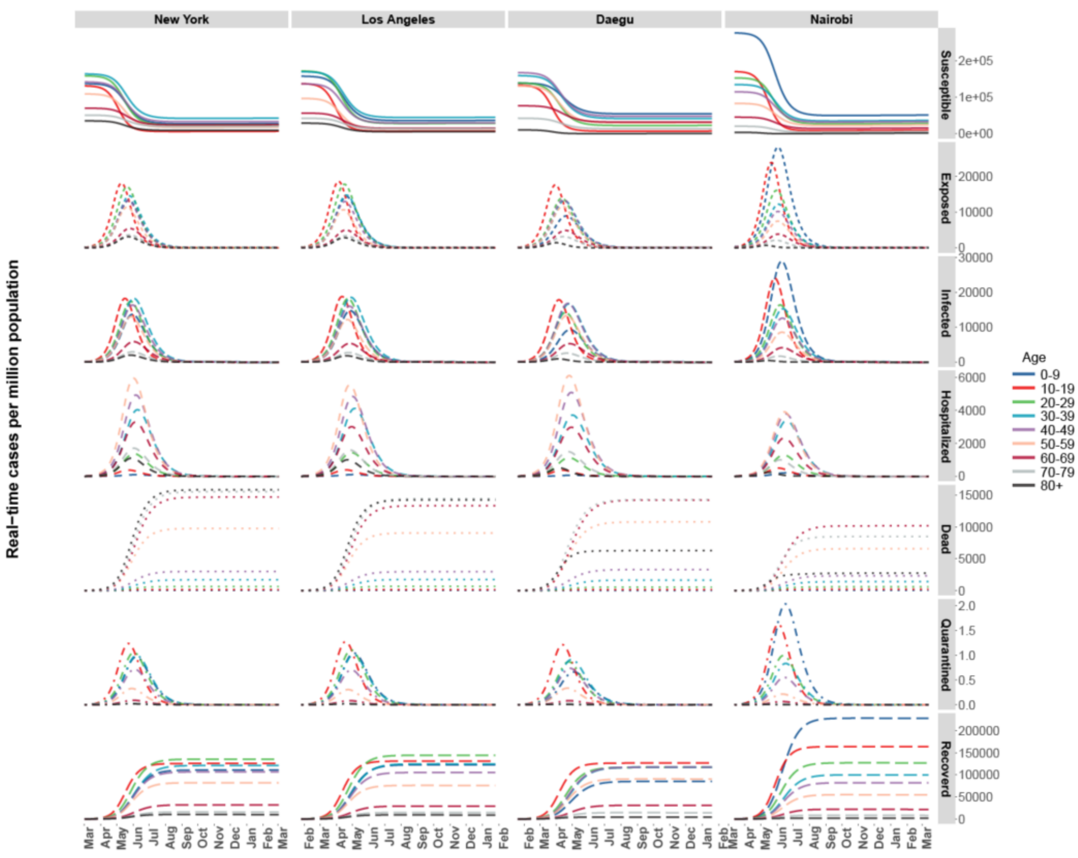

Figure 3 Real-time cases of different states under the risk of COVID-19 without policy interventions.

We find that school closure avoids 12%, 21%, 14% and 15% of infection in Nairobi, Daegu, New York and Los Angeles (Figure 4). A strategy of 50% of the population working from home only avoided 5% infection in Nairobi and 9%-10% in the other three cities. This clarifies how important it is to combine working remotely with other mitigation strategies to flatten the curve. An 80% population working from home strategy results (Scenario C) in 77% more avoided infection than that in Scenario B. A 50% reduction in other mobility helped Nairobi flatten the curve more effectively than the same degree of the working from home strategy. In contrast, a 10%

daily quarantine rate averted (Scenario F) 45%-53% of all infections, which was more effective than a strict single social distancing strategy. The sustained combination of all four interventions together reduced the fatality rates by 96%-99% (Scenario G).

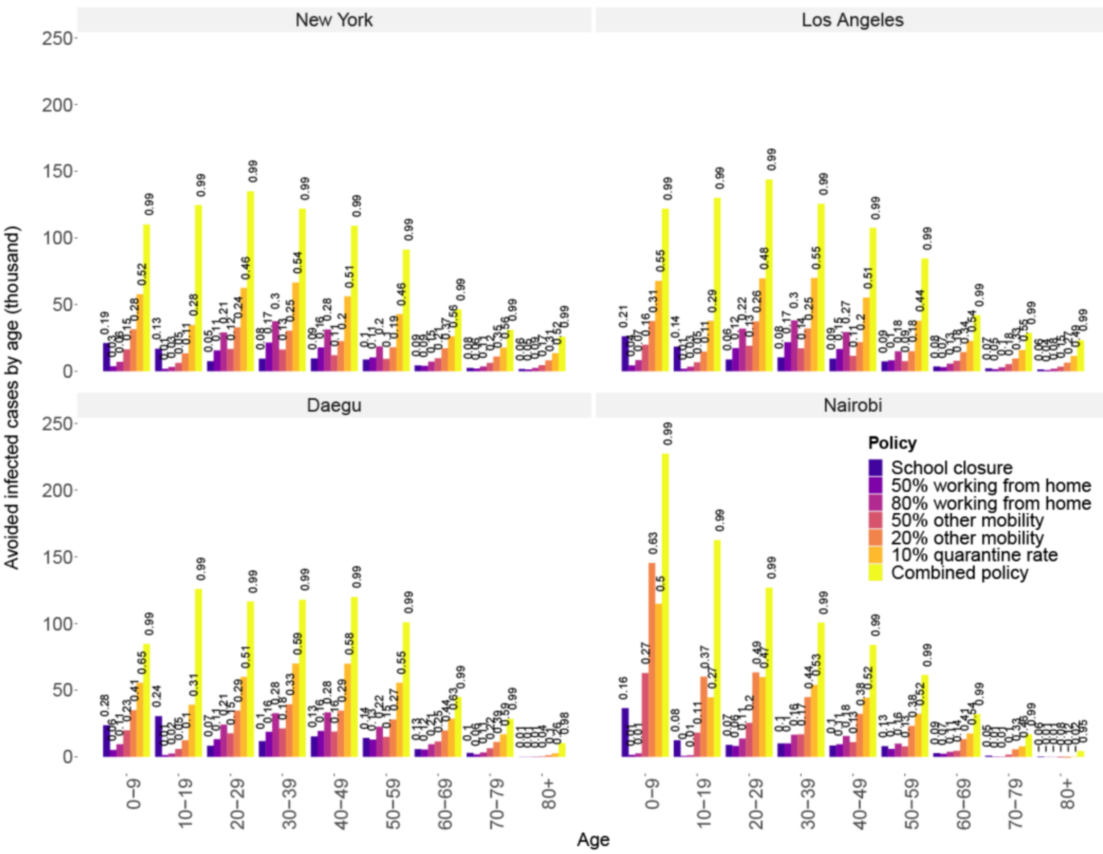

Figure 4 Avoided infected cases of the five policy interventions (Scenarios A – G in Table 2) by age in the four cities.

The effects of these five interventions also generated diverse effects for susceptible individuals in different ages. School closures resulted in largest impacts on the younger population aged from 0-19 and 50-59 years old population in four cities. The impact on the 50-59 year old group is an interesting interaction of the lower population exposure and the increasing susceptibility of this age group. A 50% work from home policy can avoid 14% of the infections in for the middle-age population (20-59 years old) in Daegu, Los Angeles and New York, while only avoid 9% infection for middle-age population in Nairobi since the transmission rates of working people were lower than the other three cities. A 50% reduction in other mobility can result in most avoided infection in older-age population (60 years and older) which accounted for 12%, 17%, 19% and 21% of the no intervention scenario.

The effectiveness of each intervention varied by the age of population. A 10% quarantine of the infected across all age groups was the most effective strategy in each of the four cities, which avoided 40%-50% of total infections for people who were 20-69 years old compared to the no intervention baseline. The quarantine strategy curbed the epidemic most quickly, however the spread of COVID-19 can then bounce back if we relaxed these interventions after 8 months (Figure 2a in Appendix 1).

A key finding of this work is that a combination of these four strategies could avoid 98%-99% over an 8 months intervention. It is important to take note of this finding, because as of this writing, most U. S. cities have been under quarantine for less than one month, and already political and social backlash against the strategies is growing in some communities and among some politicians. Under Scenario F and Scenario G, the four cities could be hit by second wave. Therefore, it is critical to maintain the interventions to avoid a second wave of COVID-19, which has now been mildly observed in China. We observe significant variations in the impacts of the different social distancing strategies, while the quarantine strategies (Scenario F and G) show are more uniform effect. With combination of these four interventions, limited age-specific effects were observed in the simulation. A moderate social distancing combined with high quarantine intervention (Scenario G) was effective enough to curb the spread of epidemic in 3 months (Appendix 1).

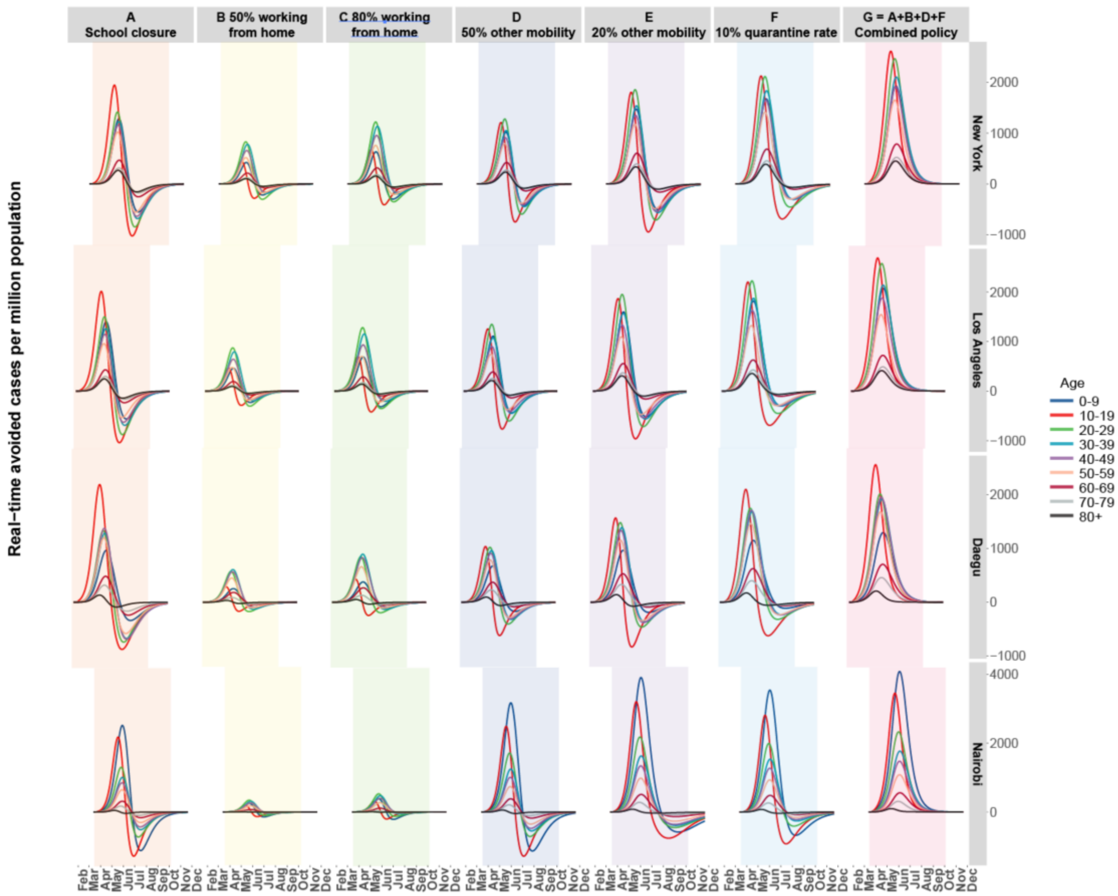

Figure 5 Time-series of the avoided cases distribution in the four cities by age. The shadowed regions represent the periods of interventions. Here the interventions take effects for 8 months since the intervention started after a week of the first case detected in each city.

In the simulation of five interventions, a 10% quarantine rate avoided over 50% of the spread of the epidemic without totally shutting down the economy. Therefore, it is going to be beneficial for cities that are capable to diagnose exposed individuals and implement a detail epidemiological survey and then quarantine them strictly to avoid secondary transmission. However, social distancing should be combined to avoid fast hitting-back effect shown in Figure 5. This strategy together with moderate social distancing can effectively avoid strict social distancing and city lockdown interventions which could be costly to the economy.

2. Age-specific benefits of intervention timing

Figure 6 shows the avoided dead, hospitalized and infected cases of COVID-19 under 1-week earlier interventions compared with the timing of their current policy interventions that were already implemented in the four cities.

An earlier intervention avoided 42%, 33%, 5%, and 16% deaths related to COVID-19 in Los Angeles, New York, Daegu and Nairobi. The earlier intervention benefited population aged 80 years and older the most in Nairobi, and Daegu, while the intervention avoided more deaths among population aged 10-19 years old in New York and Los Angeles. A similar trend can also be found in the containment effect of infection of the epidemic. By intervening 1-week earlier, Daegu avoids 250 cases of infection, which accounted for 5% of the infection in the business-as-usual (BAU) scenario (policy actions implemented in the real case). We find that Los Angeles and New York could have avoided 43% and 38% of infection if the interventions were introduced 1-week earlier. The earlier intervention strategy also mitigated the overwhelming requirement of hospital beds. Without implementing strict containment strategies, moving intervention earlier could help flatten the curve to certain degree depending on the timing of BAU interventions taking effects.

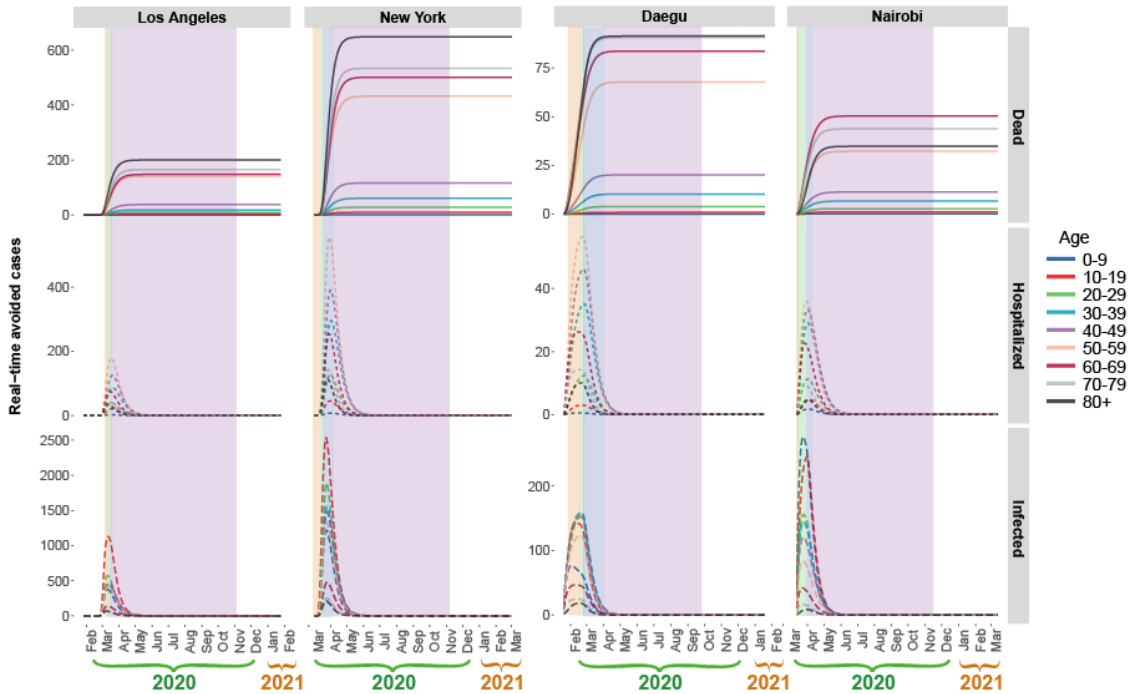

Figure 6 Age-specific effects of 1-week earlier intervention in four cities. The four colors of shadows represent four interventions and the widths of the shadows represent the duration of each intervention.

Discussion

We developed, documented, and provided an open source model (available at https://github.com/HaoYinV/SEIR-HQD and at http://rael.berkeley.edu) which we utilized to examine the effects of different intervention strategies as nations manage risks to different age groups, and as sub-national regions work to curb the spread of COVID-19, and avoid the risks of a second reinfection wave. We tracked and modeled interventions in Daegu, South Korea, Nairobi, Kenya, and in Los Angeles and New York in the USA, to capture the effectiveness of these interactions between different public health interventions and population demographics. We explored the age-specific effects of COVID-19 interventions and their combination could differ depending on the age structure of susceptible population. We found that social distancing strategy in different location might generate stronger age-differential effects compared with the quarantine strategy.

Nairobi might have more infected cases than New York, Los Angeles and Daegu since younger people are relatively more active with higher transmission rates in no intervention scenario, however, there were more cases of fatality and hospitalization in the three cities with an ageing population. Under five intervention scenarios, we found that school closure avoided more infection of population aged 0-19 years old, while working from home and reduction in other mobility had more averted infection in middle aged population. This leads to significantly reductions in death rates, which a strongly skewed to the younger and middle population, more actions are needed for the older population.

In addition, we find the need to guard by sustaining interventions in Nairobi that could otherwise experience a second wave of infections that would hit faster than in the other three cities owing to the higher transmission rates in younger people. Cities with older population should take actions by reducing mobility in the older population and encouraging younger population to go to work combining with social distancing strategy and growing quarantine rates. We showed that it was possible to contain the pandemic with strategy of high quarantine rate together with moderate social distancing in working and other mobility which could largely avoid the costly influence on the national and global economy. Earlier intervention could help flatten the curve in Los Angeles and New York the most due to the relative slow actions since the first case was detected than other two cities. We did not find the substantial difference of the early intervention on population in different ages in the simulations.

There is limited study showing that susceptibility and transmissibility vary with the age of the population at risk.[9] The SEIR-HQD model was based on assumption that the transmissibility only depends on the contact rates and population sizes in each age group. In our model, we assume the quarantine only happened to people who showed symptoms, whereas, the quarantine strategy could even expand to the exposed but have no symptom yet. Therefore, an expanding quarantine intervention might have even larger effects than the results from our simulations. Since there was no city-specific fatality rates in each city, we adopted the age-specific fatality of China in four cities that was adjusted for censoring demographic information without the consideration of the medical capacity and facility.[1] In addition, other environmental risks, such as air pollution, might have significant impacts on the fatality rate of COVID-19 geographically.[22] A unified age-specific fatality rate might over- or underestimate the estimates of deaths in the four cities. In our model, we did not consider the population dynamics during the pandemic. Next step, we will further incorporate the impacts of population movement and air quality inside the SEIR-HQD model.

In conclusion, the combination of moderate social distancing and high quarantine rate could avoid over 90% of the infection and flatten the epidemic curve in a short period of time. Social distancing might have age-specific effects; therefore, cities with a high proportion of ageing population should reduce their mobility and protect them from younger population who tend to have higher transmission rates. Cities with younger population should be more careful about the second hit, while cities with ageing population should prepare more hospital beds and resources.

Declaration of interests

We declare no competing interests.

Open Access Code and Data sharing

The data used in this study is publicly available.[12] The modeling code and estimation process are available online at https://github.com/HaoYinV/SEIR-HQD and http://rael.berkeley.edu.

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References

1 Verity R, Okell LC, Dorigatti I, *et al.* Estimates of the severity of coronavirus disease 2019 : a model-based analysis. *Lancet Infect Dis* 2020. DOI:10.1016/S1473-3099(20)30243-7.

2 Santesmasses D, Castro JP, Zenin AA, *et al.* COVID-19 is an emergent disease of aging. *medRxiv* 2020; : 2020.04.15.20060095.

3 Dowd JB, Rotondi V, Adriano L, *et al.* Demographic science aids in understanding the spread and fatality rates of COVID-19. *medRxiv* 2020. DOI:10.1101/2020.03.15.20036293.

4 Flaxman S, Mishra S, Gandy A, *et al.* Report 13: Estimating the number of infections and the impact of non-pharmaceutical interventions on COVID-19 in 11 European countries. 2020.

5 Wu JT, Leung K, Leung GM. Nowcasting and forecasting the potential domestic and international spread of the 2019-nCoV outbreak originating in Wuhan, China: a modelling study. *Lancet* 2020. DOI:10.1016/S0140-6736(20)30260-9.

6 Bayham J, Fenichel EP. Impact of school closures for COVID-19 on the US health-care workforce and net mortality: a modelling study. *Lancet Public Heal* 2020; published online April 11. DOI:10.1016/S2468-2667(20)30082-7.

7 Ferguson NM, Laydon D, Nedjati-Gilani G, *et al.* Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand. *ImperialAcUk* 2020. DOI:10.25561/77482.

8 Tian H, Liu Y, Li Y, *et al.* An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. *Science* 2020. DOI:10.1126/science.abb6105.

9 Prem K, Liu Y, Russell TW, *et al.* The effect of control strategies to reduce social mixing on outcomes of the COVID-19 epidemic in Wuhan, China: a modelling study. *Lancet Public Heal* 2020. DOI:10.1016/s2468-2667(20)30073-6.

10 Leung K, Wu JT, Liu D, Leung GM. First-wave COVID-19 transmissibility and severity in China outside Hubei after control measures, and second-wave scenario planning: a modelling impact assessment. *Lancet* 2020; published online April 11. DOI:10.1016/S0140-6736(20)30746-7.

11 Vahia I V., Blazer DG, Smith GS, *et al.* COVID-19, Mental Health and Aging: A Need for New Knowledge to Bridge Science and Service. *Am J Geriatr Psychiatry* 2020. DOI:10.1016/j.jagp.2020.03.007.

12 Dong E, Du H, Gardner L. An interactive web-based dashboard to track COVID-19 in real time. Lancet Infect. Dis. 2020. DOI:10.1016/S1473-3099(20)30120-1.

13 Dyer O. Covid-19: US testing ramps up as early response draws harsh criticism. *BMJ* 2020. DOI:10.1136/bmj.m1167.

14 Boccia S, Ricciardi W, Ioannidis JPA. What Other Countries Can Learn From Italy During the COVID-19 Pandemic. *JAMA Intern Med* 2020; published online April 7. DOI:10.1001/jamainternmed.2020.1447.

15 Centers for Disease Control and Prevention. Recommendation Regarding the Use of Cloth Face Coverings, Especially in Areas of Significant Community-Based Transmission. CDC website. 2020. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/cloth-face-cover.html.

16 Liu T, Hu J, Kang M, *et al.* Transmission dynamics of 2019 novel coronavirus (2019-nCoV). 2020.

17 Backer JA, Klinkenberg D, Wallinga J. Incubation period of 2019 novel coronavirus (2019-nCoV) infections among travellers from Wuhan, China, 20-28 January 2020. *Euro Surveill* 2020. DOI:10.2807/1560-7917.ES.2020.25.5.2000062.

18 Cao Z, Zhang Q, Lu X, *et al.* Incorporating human movement data to improve epidemiological estimates for 2019-nCoV. *medRxiv* 2020.

19 Bi Q, Wu Y, Mei S, *et al.* Epidemiology and Transmission of COVID-19 in Shenzhen China: Analysis of 391 cases and 1,286 of their close contacts. *medRxiv* 2020. DOI:10.1101/2020.03.03.20028423.

20 Abbott S, Hellewell J, Munday J, Funk S. The transmissibility of novel Coronavirus in the early stages of the 2019-20 outbreak in Wuhan: Exploring initial point-source exposure sizes and durations using scenario analysis. *Wellcome Open Res* 2020. DOI:10.12688/wellcomeopenres.15718.1.

21 Prem K, Cook AR, Jit M. Projecting social contact matrices in 152 countries using contact surveys and demographic data. *PLoS Comput Biol* 2017. DOI:10.1371/journal.pcbi.1005697.

22 Wu X, Nethery RC, Sabath BM, Braun D, Dominici F. Exposure to air pollution and COVID-19 mortality in the United States. *medRxiv* 2020.

<u>**Appendices:**</u>

Impacts of Early Interventions on the Age-Specific Incidence of COVID-19 in New York, Los Angeles, Daegu and Nairobi

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Appendix 1

1. Population age structure

Compared with New York, Los Angeles and Daegu, the population in Nairobi was much younger (Figure 1a).

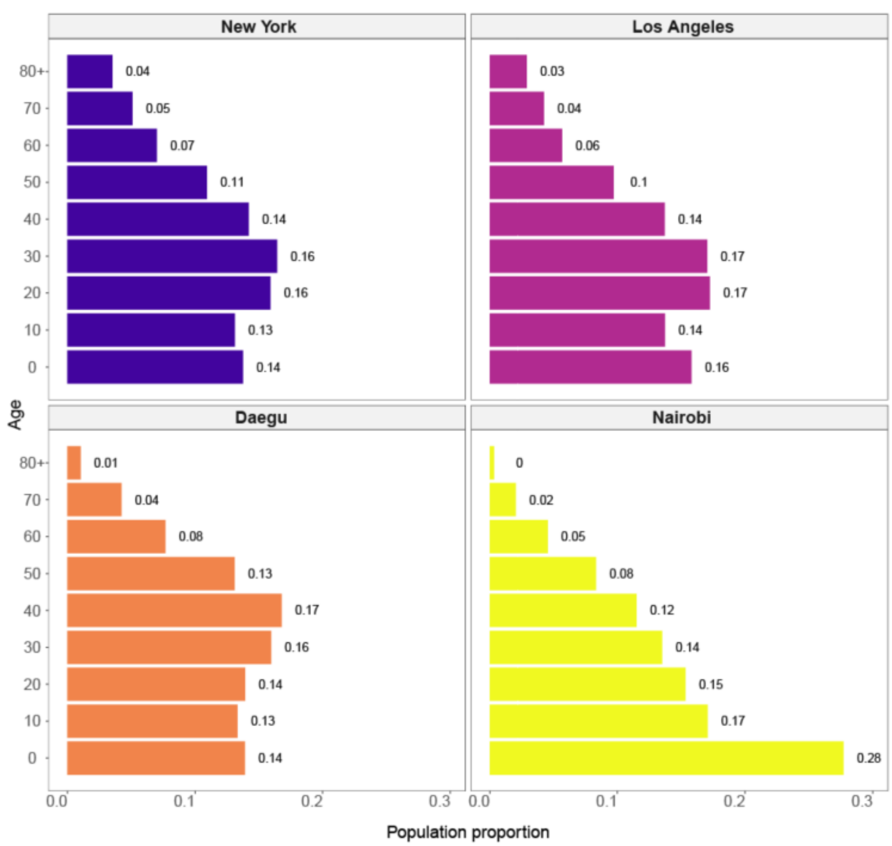

Figure 1a Population age structure in four cities

2. Birth and death rates

City	New York	Los Angeles	Daegu	Nairobi
Birth rate per 1000 people/year	11.8	11.8	7.4	29.3

Table 1a Birth rates in the four cities

In our simulation we also consider the dynamics of population birth and death rates without the risks of COVID-19. In addition, the population will transit from one age group to another over time of the simulation.

City / Age	New York	Los Angeles	Daegu	Nairobi
0-9	0.0013	0.0013	0.0003	0.0036
10-19	0.0004	0.0004	0.0003	0.0017
20-29	0.0010	0.0010	0.0005	0.0036
30-39	0.0016	0.0016	0.0010	0.0064
40-49	0.0030	0.0030	0.0023	0.0103
50-59	0.0064	0.0064	0.0050	0.0185
60-69	0.0126	0.0126	0.0133	0.0407
70-79	0.0266	0.0266	0.0460	0.0930
80+	0.0709	0.0709	0.0853	0.1346

Table 2a Death rates by age in the four cities

Table 3a Hospitalization rate by age in the four cities

Table 4a Fatality rate by age in the four cities

3. Transmission rates

Transmission rate	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80+
0-9	0.1274	0.0302	0.0231	0.0507	0.0255	0.0132	0.0076	0.0026	0.0026
10-19	0.0354	0.2962	0.0383	0.0371	0.0474	0.0159	0.0046	0.0022	0.0022
20-29	0.0177	0.0514	0.1446	0.0663	0.0515	0.0323	0.0050	0.0017	0.0017
30-39	0.0337	0.0288	0.0463	0.0876	0.0535	0.0267	0.0070	0.0018	0.0018
40-49	0.0202	0.0459	0.0384	0.0557	0.0743	0.0301	0.0061	0.0025	0.0025
50-59	0.0225	0.0422	0.0431	0.0451	0.0526	0.0563	0.0120	0.0031	0.0031
60-69	0.0131	0.0119	0.0139	0.0208	0.0169	0.0170	0.0233	0.0048	0.0048
70-79	0.0076	0.0117	0.0056	0.0095	0.0143	0.0100	0.0112	0.0128	0.0128
80+	0.0076	0.0117	0.0056	0.0095	0.0143	0.0100	0.0112	0.0128	0.0128

Table 5a Transmission rates by age in New York

Transmission rate	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80+
0-9	0.1260	0.0298	0.0229	0.0501	0.0252	0.0130	0.0075	0.0025	0.0025
10-19	0.0350	0.2929	0.0379	0.0367	0.0468	0.0157	0.0046	0.0021	0.0021
20-29	0.0175	0.0509	0.1430	0.0656	0.0509	0.0319	0.0049	0.0017	0.0017
30-39	0.0333	0.0285	0.0458	0.0867	0.0529	0.0264	0.0070	0.0018	0.0018
40-49	0.0199	0.0454	0.0380	0.0551	0.0735	0.0297	0.0060	0.0024	0.0024

50-59	0.0223	0.0417	0.0426	0.0446	0.0520	0.0557	0.0119	0.0030	0.0030
60-69	0.0130	0.0118	0.0137	0.0206	0.0167	0.0168	0.0231	0.0048	0.0048
70-79	0.0075	0.0116	0.0055	0.0094	0.0141	0.0098	0.0111	0.0126	0.0126
80+	0.0075	0.0116	0.0055	0.0094	0.0141	0.0098	0.0111	0.0126	0.0126

Table 6a Transmission rates by age in Los Angeles

Transmission rate	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80+
0-9	0.0811	0.0186	0.0138	0.0343	0.0218	0.0096	0.0048	0.0020	0.0020
10-19	0.0284	0.3078	0.0308	0.0308	0.0470	0.0168	0.0037	0.0023	0.0023
20-29	0.0123	0.0417	0.1265	0.0615	0.0500	0.0351	0.0059	0.0020	0.0020
30-39	0.0322	0.0254	0.0437	0.0933	0.0554	0.0283	0.0089	0.0025	0.0025
40-49	0.0199	0.0463	0.0366	0.0577	0.0808	0.0317	0.0067	0.0032	0.0032
50-59	0.0190	0.0414	0.0423	0.0460	0.0551	0.0575	0.0113	0.0038	0.0038
60-69	0.0096	0.0090	0.0125	0.0225	0.0176	0.0163	0.0189	0.0044	0.0044
70-79	0.0069	0.0108	0.0056	0.0114	0.0154	0.0111	0.0106	0.0122	0.0122
80+	0.0069	0.0108	0.0056	0.0114	0.0154	0.0111	0.0106	0.0122	0.0122

Table 7a Transmission rates by age in Daegu

Transmission rate	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80+
0-9	0.2020	0.0541	0.0351	0.0397	0.0160	0.0075	0.0040	0.0012	0.0012
10-19	0.0642	0.2993	0.0419	0.0278	0.0223	0.0069	0.0025	0.0010	0.0010
20-29	0.0296	0.0559	0.1129	0.0483	0.0286	0.0131	0.0034	0.0005	0.0005
30-39	0.0378	0.0277	0.0358	0.0491	0.0317	0.0119	0.0031	0.0004	0.0004
40-49	0.0247	0.0341	0.0240	0.0338	0.0334	0.0132	0.0029	0.0004	0.0004
50-59	0.0197	0.0249	0.0188	0.0208	0.0230	0.0129	0.0036	0.0006	0.0006
60-69	0.0129	0.0111	0.0075	0.0099	0.0080	0.0062	0.0025	0.0007	0.0007
70-79	0.0076	0.0120	0.0024	0.0031	0.0036	0.0031	0.0021	0.0012	0.0012
80+	0.0076	0.0120	0.0024	0.0031	0.0036	0.0031	0.0021	0.0012	0.0012

Table 8a Transmission rates by age in Nairobi

4. Real-time infected cases in 7 scenarios

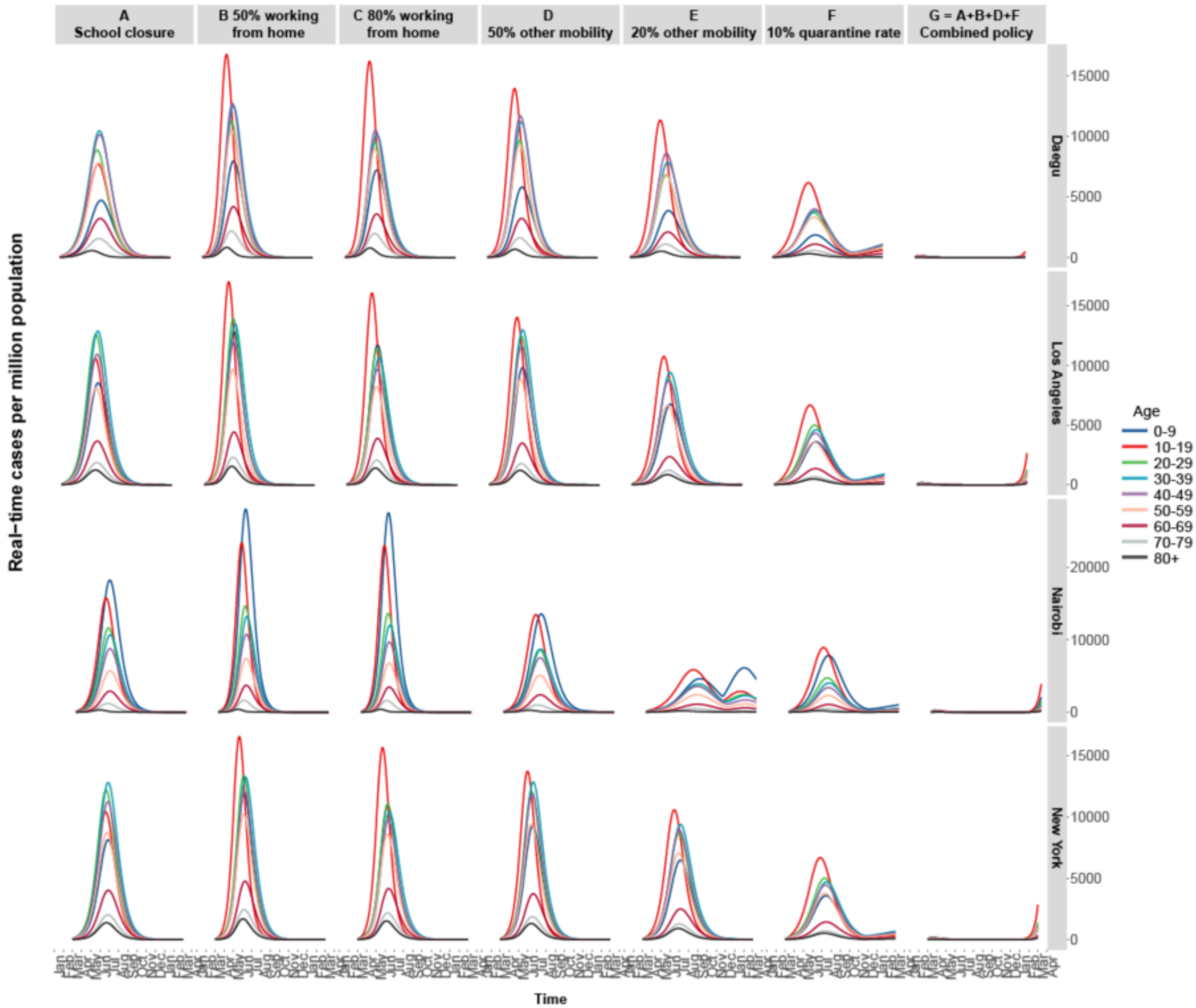

Figure 2a The infected cases of four cities in 7 scenarios

5. Policy database in each city

City	Date	Event	Policy details	References
Los Angeles	1/26/2020	First case report		https://coronavirus.jhu.edu/map.html
Los Angeles	3/4/2020	Declare local emergency		https://www.lamayor.org/COVID19Orders
Los Angeles	3/4/2020	State order	All residents of the state to stay home exept essential needs	https://www.gov.ca.gov/wp-content/uploads/2020/03/EO-N-33-20-COVID-19-HEALTH-ORDER-03.19.2020-002.pdf
Los Angeles	3/5/2020	Californians for free test		https://www.cdph.ca.gov/Programs/OPA/Pages/NR20-012.aspx
Los Angeles	3/12/2020	City guidelines	1. Self-quarantine for employees with symptoms; 2. Respiratory etiquette, social distancing and hand hygiene; 3. Thorough cleaning of commonly touched surfaces; 4. Disseminate updates in work spaces; 5. Cancel all non-essential public community events; 6. Avoid close contact of vulnerable individuals; 7. stagger visitors in public gathering places; 8. Hand washing and sanitizer available. 8. Cancel non-essential travels; 9. Develop telecommuting plans	https://www.lamayor.org/sites/g/files/wph446/f/article/files/Mayor%20Memo%20-COVID-19%20LA%20City%20Guidelines.pdf
Los Angeles	3/15/2020	New city measures	1. All bars and nightclubs were closed; 3. All restaurants and retail food facilities were prohibited; 4. All movie theaters, live performance venues, arcades, gyms were closed. 5. Violation fines or imprisonment	https://www.lamayor.org/sites/g/files/wph446/f/article/files/Mayor%20Garcetti%20Emergency%20Order%20-%20March%2015%202020.pdf
Los Angeles	3/16/2020	School closed		https://www.lamayor.org/COVID19Orders
Los Angeles	3/17/2020	Public order	1. No landlord shall evict a residential or commercial tenant during this local emergency period if the tenant is able to show an inability to pay rent due to COVID-19; 2. parking enforcement was relaxed for manufacturing or healthcare activities	https://www.lamayor.org/sites/g/files/wph446/f/page/file/CommercialEvictionMoratoriumFINAL.pdf
Los Angeles	3/19/2020	State stay home order	Stay at home except for essential goods or jobs; keep social distancing for 6 feet.	https://www.lamayor.org/sites/g/files/wph446/f/page/file/SAFER%20AT%20HOME%20ORDER%202020.03.19%20%28REV%202020.04.01%29.pdf
Los Angeles	3/21/2020	Non-essential cross-border travel suspended		https://www.dhs.gov/news/2020/03/23/fact-sheet-dhs-measures-border-limit-further-spread-coronavirus?utm_source=hp_slideshow&utm_medium=web&utm_campaign=dhsgov

Los Angeles	3/25/2020	Emergency guideline	Relaxing contracting and vehicle restrictions	https://www.lamayor.org/sites/g/files/wph446/f/page/file/20200325MemotoCityDepts.pdf
Los Angeles	4/1/2020	Public order: Safer at home	Safer at home	https://covid19.ca.gov/
Los Angeles	4/3/2020	Facemasks		https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/cloth-face-cover.html
New York	3/2/2020	First case report		https://coronavirus.jhu.edu/map.html
New York	3/5/2020	City public order	The vulnerable are required to stay home; educators, first responders, and healthcare workers are subject to be tested for COVID-19	https://www1.nyc.gov/assets/doh/downloads/pdf/imm/order-of-the-commissioner-to-all-educators-first-responders-healthcare-covid19.pdf
New York	3/6/2020	Guidance for testing and quarantine		https://www.governor.ny.gov/news/statement-new-york-state-department-health-commissioner-doctor-howard-zucker
New York	3/10/2020	Guidance for cleaning and disinfection of public and private facilities	Instructions for hand hygiene, respiratory hygine, routine cleaning	https://www.agcnys.org/wp-content/uploads/cleaning_guidance_general_building-NYSDOH.pdf
New York	3/7/2020	State of disaster emergency		https://www.governor.ny.gov/news/no-20214-continuing-temporary-suspension-and-modification-laws-relating-disaster-emergency
New York	3/16/2020	School closed		https://www.governor.ny.gov/news/governor-cuomo-signs-executive-order-closing-schools-statewide-two-weeks
New York	3/17/2020	Bars and restaurant closed; mandatory workforce reduce by 75%		https://www.governor.ny.gov/news/video-audio-photos-rush-transcript-governor-cuomo-signs-executive-order-mandating-businesses
New York	3/21/2020	Non-essential cross-border travel suspended		https://www.dhs.gov/news/2020/03/23/fact-sheet-dhs-measures-border-limit-further-spread-coronavirus?utm_source=hp_slideshow&utm_medium=web&utm_campaign=dhsgov
New York	3/22/2020	State Pause' Executive Order	1. 100% closure of non-essential businesses statewide; 2. Provide new protections for vulnerable populations; 3. 90-day moratorium on residential or commercial evictions; 4. Encourage companies to produce PPE products	1. https://www1.nyc.gov/assets/home/downloads/pdf/executive-orders/2020/eeo-98.pdf; 2. https://coronavirus.health.ny.gov/new-york-state-pause
New York	3/25/2020	Car-free streets		https://nyc.streetsblog.org/2020/03/25/here-are-the-four-streets-de-blasio-will-close-to-cars-for-four-days/
New York	3/27/2020	Guidance to shut down a business	1. workforce reduction; 2. shut down non-essential construction	https://esd.ny.gov/guidance-executive-order-2026

New York	4/2/2020	City calls for medical essentials	1. Face covering; 2. Expanding DOE meal hubs; 3. Loans for small business; 4. Get notification from government on the latest developments	https://coronavirus.health.ny.gov/system/files/documents/2020/03/cleaning_guidance_general_building.pdf
New York	4/7/2020	State executive order	Continuing Temporary Suspension and Modification of Laws Relating to the Disaster Emergency	https://www.governor.ny.gov/news/no-20214-continuing-temporary-suspension-and-modification-laws-relating-disaster-emergency
Daegu	1/20/2020	First case report		
Daegu	1/28/2020	All-out measures for COVID-19	1. Third-level emergency; 2. full inspection on all travellers who entered from Wuhan; 3. Detail of the fourth patient's epidemiological investigation was revealed to the public. 4. Encourage face masks	https://www.mohw.go.kr/eng/nw/nw0101vw.jsp?PAR_MENU_ID=1007&MENU_ID=100701&page=3&CONT_SEQ=352623
Daegu	2/7/2020	Free disgnostic testing	testing capacity increased to 15000 per day in March	http://ncov.mohw.go.kr/en/baroView.do?brdId=11&brdGubun=111&dataGubun=&ncvContSeq=&contSeq=&board_id=
Daegu	2/12/2020	Control measures for incoming passengers from abroad	All passengers are tested and positive ones will be transferred to a hospital or living center; negative people will be quarantined for 14 days.	http://ncov.mohw.go.kr/en/baroView.do?brdId=11&brdGubun=111&dataGubun=&ncvContSeq=&contSeq=&board_id=
Daegu	2/20/2020	People to stay at home	1. Cancel all non-essential gatherings; 2. Stay home except to purchase necessities, to get medical care, or to go to work; 3. keep 2 meter distance; 4. disinfect home	
Daegu	2/21/2020	School and public spaces closed		
Daegu	2/23/2020	Declared highest alert of COVID-19		https://www.bbc.com/news/world-asia-51603251
Daegu	2/25/2020	Epidemic survey when positive cases are detected		http://ncov.mohw.go.kr/en/baroView.do?brdId=11&brdGubun=111&dataGubun=&ncvContSeq=&contSeq=&board_id=
Daegu	3/7/2020	Quarantine system		http://ncov.mohw.go.kr/en/baroView.do?brdId=11&brdGubun=111&dataGubun=&ncvContSeq=&contSeq=&board_id=
Daegu	3/25/2020	Enhanced social distancing campaign		https://www.mohw.go.kr/eng/nw/nw0101vw.jsp?PAR_MENU_ID=1007&MENU_ID=100701&page=1&CONT_SEQ=353989
Daegu	4/1/2020	Stronger quarantine inspection measures for incoming passengers	1. preventive measures for the vulnerable; 2. plan to conduct additional nationwide investigation on designated hospitals; 3. Release the list of community treatment centers and hospitals; 4. provide social emergency service	https://www.mohw.go.kr/eng/nw/nw0101vw.jsp?PAR_MENU_ID=1007&MENU_ID=100701&page=2&CONT_SEQ=353495
Daegu	4/4/2020	Extending Intensive social distancing		https://www.mohw.go.kr/eng/nw/nw0101vw.jsp?PAR_MENU_ID=1007&MENU_ID=100701&page=1&CONT_SEQ=353953

Daegu	4/9/2020	Supporting online school opening and religious activities	1. Delaying start of new school year; 2. Measures to block inflow in response of the epidemic; 3.Avoid cluster transmission, sufficient communication with religious community; 4. supporting masks for the vulnerable.	https://www.mohw.go.kr/eng/nw/nw0101vw.jsp?PAR_MENU_ID=1007&MENU_ID=100701&page=2&CONT_SEQ=353618
Nairobi	3/13/2020	First case report		
Nairobi	3/15/2020	Block entry for non-residents		https://www.bbc.com/news/world-africa-51917920
Nairobi	3/16/2020	Self-quarantine is required after entering the country		https://www.aljazeera.com/news/2020/03/kenya-blocks-entry-residents-virus-response-200315154944348.html
Nairobi	4/1/2020	Tax relief measures	1. Reduction in income tax rate, turnover tax rate; 2. reduction in the salaries of the senior national executives; 3. encourage people work from home; 4. lower interest rate; 5. recruitment of additional health workers; 6. wash hand frequently, cover mouth and nose when coughing and sneezing	https://home.kpmg/xx/en/home/insights/2020/04/flash-alert-2020-139.html
Nairobi	4/4/2020	Waive loans, secure food supply and increase testing		https://www.president.go.ke/2020/04/04/africa-to-pursue-loan-waivers-as-safeguard-against-adverse-economic-impact-of-coronavirus/
Nairobi	4/7/2020	Stop traveling in and out Nairobi area; wearing face masks; stop shaking hands		https://www.president.go.ke/2020/04/07/president-kenyatta-urges-kenyans-to-observe-government-directives-on-coronavirus/
Nairobi	4/9/2020	Production and use of face masks, increasing tests of COVID-19		https://www.dentonshhm.com/en/insights/articles/2020/april/9/supporting-you-through-covid-19-updates-from-the-kenya-government