Estimating the transmission dynamics of Omicron in Beijing, November to December 2022

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Abstract

We tracked the effective reproduction number R_t of Omicron BF.7 in Beijing in November – December 2022 by fitting a transmission dynamic model parameterized with real-time mobility data to (i) the daily number of new symptomatic cases on November 1-11 (when the zero-covid interventions were still strictly enforced) and (ii) the proportion of individuals who participated in online polls on December 10-14 and self-reported to have been previously test-positive. After the announcement of "20 measures", we estimated that R_t increased to 3.42 (95% CrI: 2.79 – 4.17) on November 18. Infection incidence peaked on December 10, and the cumulative infection attack rate was 42.5% (95% CrI: 20.3 – 63.9) on December 14. Surveillance programmes should be rapidly set up to monitor the evolving epidemiology and evolution of SARS-CoV-2 across China.

Word count: 127

Main Text

After implementing the "zero-COVID" strategy for more than two years, China has recently begun to adjust its COVID-19 response strategies, notably by announcing the "20 measures" on November 11 and further the "10 measures" on December 7, 2022 [1,2]. Since then, Omicron infections spread rapidly in major cities of China, including Beijing, where the Omicron subvariant BF.7 epidemic has been putting great pressure on the healthcare system since early December [3,4].

Regular mass testing and intensive contact tracing were suspended in late November and nucleic acid testing is conducted on a voluntary basis [5]. As such, the daily number of confirmed cases reported by Beijing Municipal Health Commission (BMHC, http://wjw.beijing.gov.cn/) thereafter was no longer an accurate reflection of the epidemic curve, making it difficult to assess the transmission dynamics. Here we tracked the effective reproduction number of Omicron BF.7 in Beijing in November – December 2022 using our previous epidemic nowcast framework which comprised disease transmission models parameterised with real-time mobility data [6]

The effective reproduction number R_t of Omicron in Beijing

We categorized the COVID-19 response adjustments in Beijing in three stages:

i) **Stage 1** (November 1-11): Zero-COVID strategy was strictly implemented with regular mass testing, intensive contact tracing and lockdown of residential buildings or communities once PCR-positive infections and their close contacts were traced.
ii) **Stage 2** (November 12-25): Although mass testing and contact tracing were maintained after the announcement of "20 measures" on November 11, lockdown was limited to the residential buildings or only the floors or units where PCR-positive infections lived.
iii) **Stage 3** (after November 25): The requirement of regular mass testing, intensive contact tracing and lockdown were gradually relaxed and finally suspended on November 30. The nucleic acid testing is conducted only on a voluntary basis after the announcement of "10 measures" on December 7.

We parameterised the disease transmission model with daily number of passengers from Beijing MTR, which manage 5 of 25 subway lines in Beijing (**Figure 1**). We fitted the model to two data streams to estimate effective reproduction number R_t: i) the daily number of symptomatic cases reported to BMHC between November 1 and 11 when the testing and reporting behaviour were relatively stable; and ii) the proportion of participants who reported to be ever positive by polymerase chain reaction (PCR) or rapid antigen test (RAT) since November 1, by convenience sampling in Weibo online polls conducted between December 10 and 14 (**Figure 1**). See **Methods** for details.

Within one week after the announcement of "20 measures", R_t increased from 1.02 (95% CrI: 0.75 – 1.29) on November 11 to 3.42 (95% CrI: 2.79 – 4.17) on November 18 (**Figure 2**). With the increasing number of cases, public health and social measures (PHSMs) were implemented: residents were urged to stay home over the weekend of November 19-20; 95% of staff were suggested to work from home in the week of November 21-25; kindergartens, primary and secondary schools were closed on November 21. Mobility and hence R_t dropped substantially below 1 to 0.87 (95% CrI: 0.71 – 1.01) on November 27.

However, the surge of infections saturated the capacity of PCR testing and quarantine facility in late November. The requirement of regular mass testing, intensive contact tracing and lockdown were gradually relaxed and finally suspended with the announcement of "10 measures". PHSMs were relaxed and consequently R_t increased to 2.71 (95% CrI: 2.04 – 2.89) on December 7 (**Figure 2**), which was substantially higher than R_t of 1.9 under similar PHSMs in the early stage of Hong Kong's Omicron wave in February – March 2022 [7].

Omicron infections grew rapidly again starting from early December, and many symptomatic infected individuals and their close contacts were self-isolated. At the time of writing, Beijing MTR's mobility dropped to low levels, and we estimated that R_t dropped below 1 on December 12 and R_t was 0.81 (95% CrI: 0.29 – 1.13) on December 14.

The daily incidence and cumulative infection attack rate

We estimated the daily incidence and cumulative infection attack rate from the fitted model accordingly (**Figure 2**). On November 30, when regular mass testing was suspended, we estimated the daily number of infections was 62,531 (95% CrI: 26,292 – 142,613). The daily incidence increased rapidly since then and peaked on December 10, with an estimated daily number of infections of 1.19 million (95% CrI: 0.55 – 1.93), i.e. 5.5% of the population.

At the time of writing, we estimated that the cumulative infection attack rate (IAR) was 42.5% (95% CrI: 20.3 – 63.9) on December 14. The daily incidence started to decrease after December 10, and we estimated the cumulative IAR would reach 58.3% (95% CrI: 36.4 – 73.6) in one week on December 21.

In the base case scenario above, we assumed each participant of the online polls underwent multiple RATs and the ascertainment probability of previous infection was 1 after November 11 (**Figure 2**). As a sensitivity analysis, we assumed that the ascertainment probability was 0.8 in the inference (**Supplementary Figure 1**). The corresponding estimated R_t was slightly higher, e.g. 3.53 (95% CrI: 2.89 - 4.29) vs. 3.42 (95% CrI: 2.79 – 4.17) on November 18, and 2.73 (95% CrI: 2.07 – 2.89) vs. 2.71 (95% CrI: 2.04 – 2.89) on December 7. The estimated cumulative IAR was higher accordingly, reaching 50.8% (95% CrI: 26.8 – 71.4) on December 14 and 64.7% (95% CrI: 44.0 – 78.2) on December 21.

Discussion

Our study tracked R_t of the Omicron BF.7 epidemic in Beijing by fitting an epidemic transmission model parameterised with mobility data to early-stage case count and recent survey data on cumulative incidence [6]. When mass testing and confirmation of all cases become impossible during the surge of infections, it is important to continuously monitor infection prevalence in the community through various surveillance programmes, e.g. REACT-type studies in the UK and Hong Kong [8,9], wastewater surveillance [10], and serological surveillance [11]. Given the roll-out of the second booster vaccines, data from such surveillance studies could also inform the assessment of vaccine effectiveness in real time [9,11].

By December 14, we estimated that the Omicron epidemic had peaked in Beijing and nearly half of the Beijing residents had been infected (**Figure 2**). Assuming no changes in PHSMs nor population behaviour, we anticipated that the number of infections would start dropping towards the end of December and the pressure on the healthcare system would be alleviated. However, vaccination should be ramped up in anticipation of upcoming waves that might arise due to increased population mixing during the Spring Festival in January 2023.

Our study has several limitations. First, passenger statistics of Beijing MTR were the only real-time mobility data we found. But Beijing MTR's passengers only accounts for about 30% of Beijing's subway volume and might not be representative of the Beijing population. Second, our estimation relied on the IARs inferred from the results of Weibo online polls. Self-reported infection status or test results can introduce bias and the ascertainment probability of infection was uncertain.

Since COVID-19 response strategies have been adjusted nationwide, infections are expected to surge in all major cities and counties across China. Surveillance programmes should be rapidly set up to monitor the spread and evolution of SARS-CoV-2 infections, and further work should be done to track the transmissibility, incidence and IAR of the epidemics.

Word count: 1179 (main text) and 653 (methods)

Methods

The transmission model

We used our previous age-structured SIR model to simulate the transmission of Omicron in Beijing [6,12]:

$$\frac{dS_a(t)}{dt} = -S_a(t)\pi_a(t)$$

$$\frac{\partial I_a(t,\tau)}{\partial t} + \frac{\partial I_a(t,\tau)}{\partial \tau} = -f_{GT}(\tau)I_a(t,\tau)$$

$$I_a(t,0) = S_a(t)\pi_a(t)$$

$$\frac{dR_a(t)}{dt} = \int_0^t f_{GT}(\tau)I_a(t,\tau)d\tau$$

$$N_a = S_a(t) + \int_0^t I_a(t,\tau)d\tau + R_a(t)$$

$$\pi_a(t) = \sum_{b=1}^{m}\int_0^t \frac{\beta_{ab}(t)}{N_b} I_b(t,\tau)d\tau$$

where

- m was the number of age groups in the population.
- $S_a(t)$ and $R_a(t)$ were the number of susceptible and removed individuals in age group a at time t.
- $I_a(t,\tau)$ was the number of infectious individuals in age group a at time t who were infected at time $t-\tau$.
- N_a was the total number of people in age group a.
- $\pi_a(t)$ was the force of infection on age group a at time t.
- f_{GT} was the probability density function of the generation time.

Following our previous framework to parameterise SARS-CoV-2 transmission models with mobility data [6], we formulated the average rate at which an individual in age group a made infectious contacts with age group b at time t, i.e., $\beta_{ab}(t)$ as

$$\beta_{ab}(t) = c_{ab}\gamma(t)\left(1-e^{-g(t)}\right)$$

where

- c_{ab} was the contact rates between age group a and age group b from Mistry et al [13].
- $g(t)$ was the normalized number of passengers of subway lines managed by Beijing MTR on day t (such that $g(t) = 1$ on November 1, 2022).
- $\gamma(t)$ was the scaling factor for the mobility data proxy $g(t)$. Given the changes in PHSMs during the weeks of November 12-25, we assumed $\gamma(t)$ was γ_1 between November 1 and 11, increased linearly between November 12 and 25 from γ_1 to γ_2, and remained at γ_2 after November 25. γ_1 and γ_2 were estimated in the parameter inference **(Supplementary Table 3)**.

The time-varying next generation matrix for this SIR model was:

$$NGM(t) = T_g \begin{bmatrix} \frac{\beta_{11}(t)S_1(t)}{N_1(t)} & \cdots & \frac{\beta_{1m}(t)S_1(t)}{N_1(t)} \\ \vdots & \ddots & \vdots \\ \frac{\beta_{m1}(t)S_m(t)}{N_m(t)} & \cdots & \frac{\beta_{mm}(t)S_m(t)}{N_m(t)} \end{bmatrix}$$

where T_g was the mean generation time.

The effective reproduction number R_t corresponded to the dominant eigenvalue of $NGM(t)$ [14,15]. The incidence rate of infection and reported onsets at time t were calculated as follows:

$$A_{infection}(t) = \sum_a S_a(t)\pi_a(t)$$

$$A_{onset}(t) = p_{report} \int_0^t f_{incubation}(t-u)\left(\sum_a A_{a,infection}(u)\right)du$$

where p_{report} was the proportion of infections ascertained and reported as symptomatic cases by Beijing Municipal Health Commission (http://wjw.beijing.gov.cn/). Similarly, the cumulative infection attack rate at time t was calculated as follows:

$$IAR(t) = \int_0^t A_{infection}(u)du$$

We assumed that the epidemic was seeded by M local infections on November 1, 2022.

The inference

The set of parameters that were subject to statistical inference, which we denoted by θ, included: (i) the seed size M; (ii) the scaling factors γ_1 and γ_2; and (iii) the ascertainment proportion p_{report} between November 1 and 11 **(Supplementary Table 3)**. We estimated θ from (i) the daily number of symptomatic cases reported to Beijing Municipal Health Commission between November 1 and 11 **(Figure 1)** and (ii) the proportion of participants who reported to be positive by PCR or RAT since November 1 in Weibo online polls conducted between December 10 and 14 **(Supplementary Table 1)**.

The likelihood function $L(\theta)$ is a product of the two components $L_1(\theta)$ and $L_2(\theta)$. $L_1(\theta)$ was formulated as below:

$$L_1(\theta) = \prod_t \left(\frac{A_{onset}(t)!}{n_{case}(t)!\left(A_{onset}(t) - n_{case}(t)\right)!} p_{report}{}^{n_{case}(t)} \left(1 - p_{report}\right)^{A_{onset}(t) - n_{case}(t)} \right)$$

where

- $n_{case}(t)$ was the daily number of symptomatic cases confirmed and reported by Beijing Municipal Health Commission between November 1 and 11.
- $A_{onset}(t)$ was daily number of infections from the model convoluted by the incubation period distribution, assuming no onset-to-confirmation delay under mass testing and intensive contact tracing between November 1 and 11.

Similarly, assuming each participant of the online polls underwent multiple RATs and the ascertainment probability of infection was 100% after November 11, $L_2(\theta)$ was formulated as below:

$$L_2(\theta) = \prod_i \prod_t \left(\frac{n_{pol}(i,t)!}{n_{pos}(i,t)!\left(n_{pol}(i,t) - n_{pos}(i,t)\right)!} IAR(t)^{n_{pos}(i,t)} \left(1 - IAR(t)\right)^{n_{pol}(i,t) - n_{pos}(i,t)} \right)$$

where

- $n_{pol}(i,t)$ was the number of participants of Weibo online poll i at time t.
- $n_{pos}(i,t)$ was the number of participants of Weibo online poll i at time t who reported to be ever tested positive by PCR or RAT since November 1.

However, the sensitivity of RAT ranges between 70% and 80% for Omicron and thus the ascertainment probability of infection could be less than 100% after November 11 [16]. In a sensitivity analysis, we assume that the ascertainment probability of infection ($p_{ascertain}$) was 80% and $L_2(\theta)$ was updated accordingly below:

$$L_2(\theta) = \prod_i \prod_t \left(\frac{n_{pol}(i,t)!}{n_{pos}(i,t)!\left(n_{pol}(i,t) - n_{pos}(i,t)\right)!} \left(p_{ascertain} IAR(t)\right)^{n_{pos}(i,t)} \left(1 - p_{ascertain} IAR(t)\right)^{n_{pol}(i,t) - n_{pos}(i,t)} \right)$$

And $L(\theta)$ was formulated as below:

$$L(\theta) = L_1(\theta) \times L_2(\theta)$$

Contributors

All authors designed the study, developed the model, analysed data, interpreted the results, and wrote the manuscript.

Declaration of interests

The authors declare no competing interests.

Data sharing statement

We collated all data from publicly available data sources. All data included in the analyses are available in the main text or the supplementary materials.

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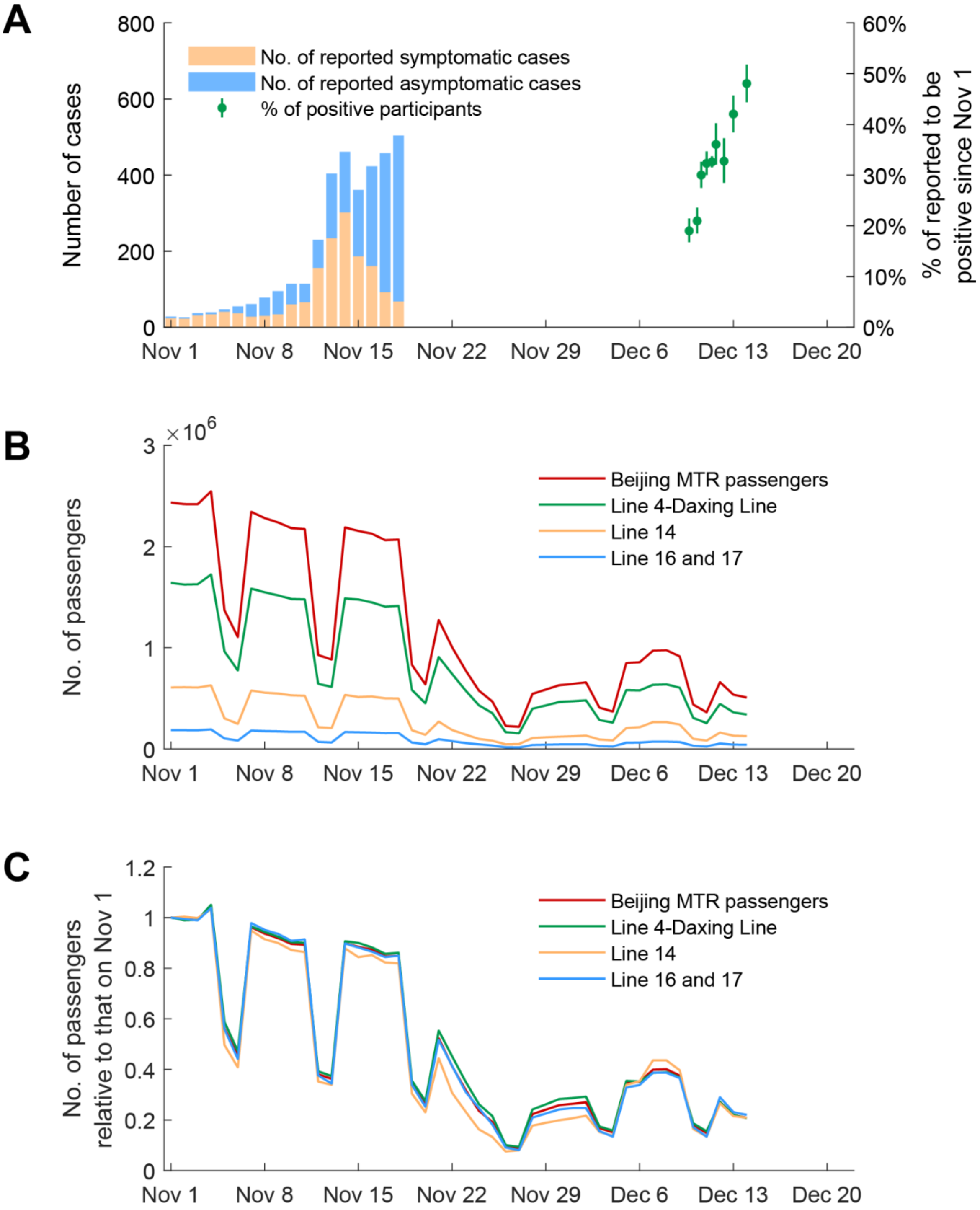


Figure 1. Data used in the inference. (A) The daily number of reported symptomatic cases between November 1 and 18 (orange), the daily number of reported asymptomatic cases between November 1 and 18 (blue), and the proportion of participants of Weibo polls who reported to be ever tested positive (PCR or RAT) between December 10 and 14 (green). The details of Weibo polls were provided in **Supplementary Table 1**. Bars in green indicate the 95% confidence interval (CI) of the proportions. **(B)** The daily number of passengers of Beijing subway lines managed by Beijing MTR, including Line 4-Daxing Line and parts of Line 14, 16 and 17. **(C)** The daily number of Beijing MTR passengers relative to that on November 1. The daily number of passengers were provided in **Supplementary Table 2**.

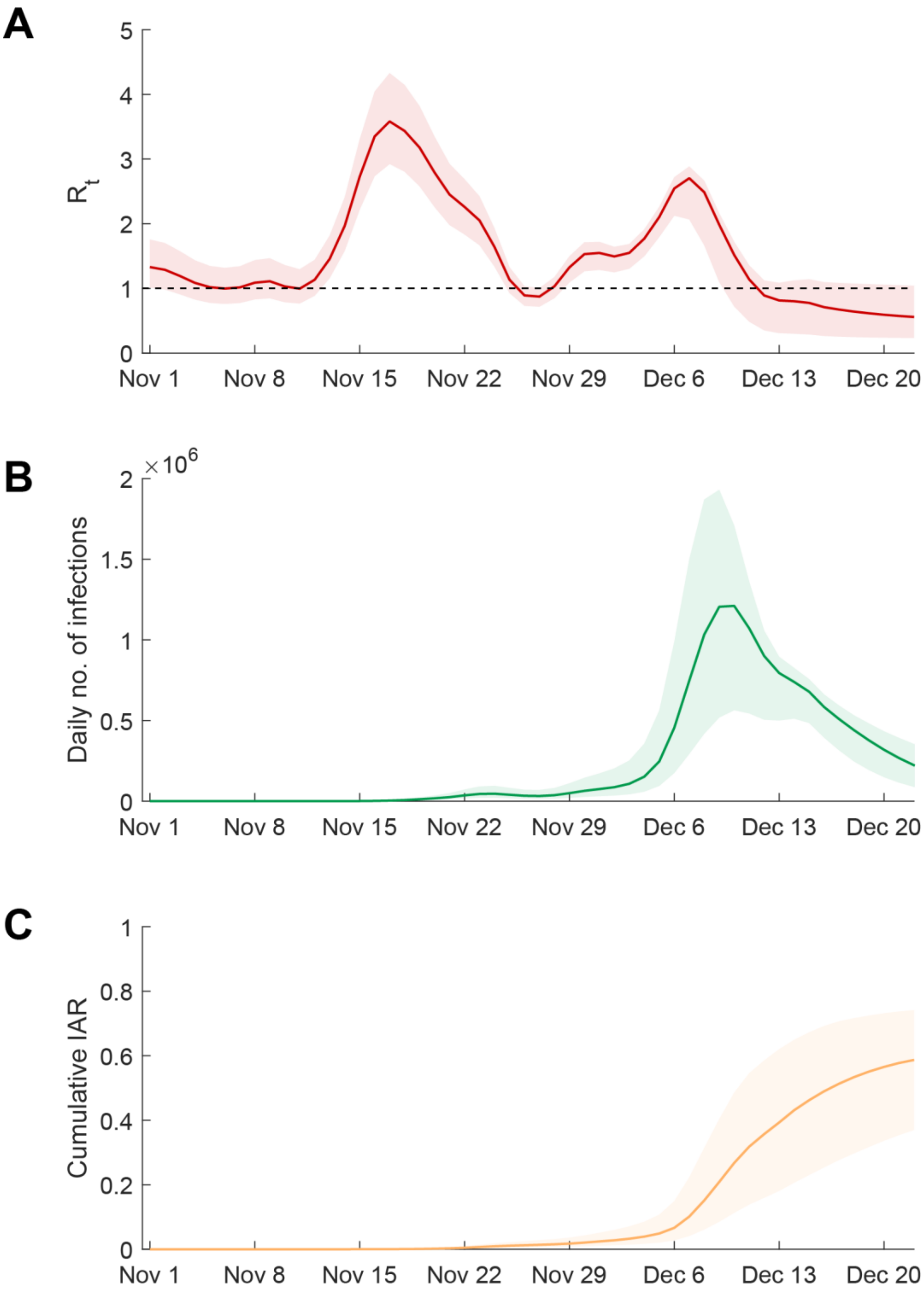


Figure 2. Estimated effective reproduction number R_t, daily incidence and cumulative infection attack rate in Beijing. (A) Estimated R_t between November 1 and December 21. The R_t between December 15 and 21 were estimated assuming that the Beijing MTR mobility and population mixing level (and hence R_t) would remain at the same levels of December 14 for the next 7 days. **(B)** Estimated daily number of infections between November 1 and December 21. **(C)** Estimated cumulative infection attack rates between November 1 and December 21. Lines indicate the mean of estimates and shades indicate the 95% credible interval (95% CrI).

Supplementary Material

Supplementary Table 1. The daily proportion of participants of Weibo online polls who reported to be tested positive by PCR or RAT since November 1 2022 in Beijing

Date	Proportion of participants who reported to be positive	No. of participants who reported to be positive	No. of participants	Source and Weibo online polls
Dec 10	0.19	211	1110	https://weibo.com/u/2987102112
Dec 10	0.21	214	1021	https://weibo.com/u/7126731879
Dec 11	0.30	373	1243	https://weibo.com/u/2987102112
Dec 11	0.32	524	1622	https://weibo.com/chinaetfs
Dec 12	0.33	2296	7043	https://weibo.com/chinaetfs
Dec 12	0.36	199	552	https://weibo.com/u/2987102112
Dec 12	0.32	150	458	https://weibo.com/u/7126731879
Dec 13	0.42	311	740	https://weibo.com/u/2987102112
Dec 14	0.48	345	718	https://weibo.com/u/2987102112

Supplementary Table 2. The daily number of passengers of Beijing subway lines managed by Beijing MTR ('0000) *

Date	Line 4 - Daxing Line	Line 14	Line 16 (north and central)	Line 17 (south)
11/1/2022	164.1	60.8	14.0	4.6
11/2/2022	162.4	61.0	13.8	4.7
11/3/2022	162.7	60.7	13.7	4.7
11/4/2022	172.4	62.8	14.5	4.8
11/5/2022	96.4	30.2	7.6	2.8
11/6/2022	77.5	24.8	5.8	2.4
11/7/2022	158.4	57.7	13.6	4.6
11/8/2022	154.8	55.6	13.4	4.3
11/9/2022	151.7	54.7	13.2	4.2
11/10/2022	148.2	53.0	12.9	4.0
11/11/2022	147.8	52.5	13.2	3.8
11/12/2022	64.4	21.4	5.1	1.9
11/13/2022	61.3	20.6	4.6	1.8
11/14/2022	148.7	53.4	12.8	3.9
11/15/2022	147.7	51.3	12.4	4.0
11/16/2022	144.8	51.8	12.1	4.0
11/17/2022	140.6	50.0	11.8	3.9
11/18/2022	141.3	49.8	11.9	3.9
11/19/2022	58.3	18.5	4.4	1.9
11/20/2022	45.1	14.0	3.2	1.5
11/21/2022	90.8	27.0	6.9	2.7
11/22/2022	74.1	18.7	5.6	2.1
11/23/2022	57.8	14.2	4.3	1.5
11/24/2022	43.1	9.9	3.4	1.2
11/25/2022	35.4	8.1	2.8	0.6
11/26/2022	16.5	4.6	1.4	0.3
11/27/2022	15.5	4.9	1.2	0.3
11/28/2022	39.7	10.8	2.9	1.0
11/29/2022	43.0	11.5	3.1	1.1
11/30/2022	46.4	12.1	3.3	1.2
12/1/2022	47.1	12.6	3.4	1.2
12/2/2022	48.0	13.2	3.4	1.2
12/3/2022	28.6	9.3	2.0	0.9
12/4/2022	26.0	8.4	1.8	0.7
12/5/2022	58.2	20.6	4.3	1.8
12/6/2022	57.8	21.5	4.4	1.9
12/7/2022	63.4	26.5	5.1	2.1
12/8/2022	63.9	26.5	5.2	2.0
12/9/2022	60.5	24.1	5.0	1.8
12/10/2022	30.7	10.0	2.2	1.0
12/11/2022	25.5	8.2	1.7	0.8
12/12/2022	44.5	16.2	4.0	1.4

12/13/2022	36.2	13.1	3.1	1.2
12/14/2022	34.0	12.7	2.9	1.2

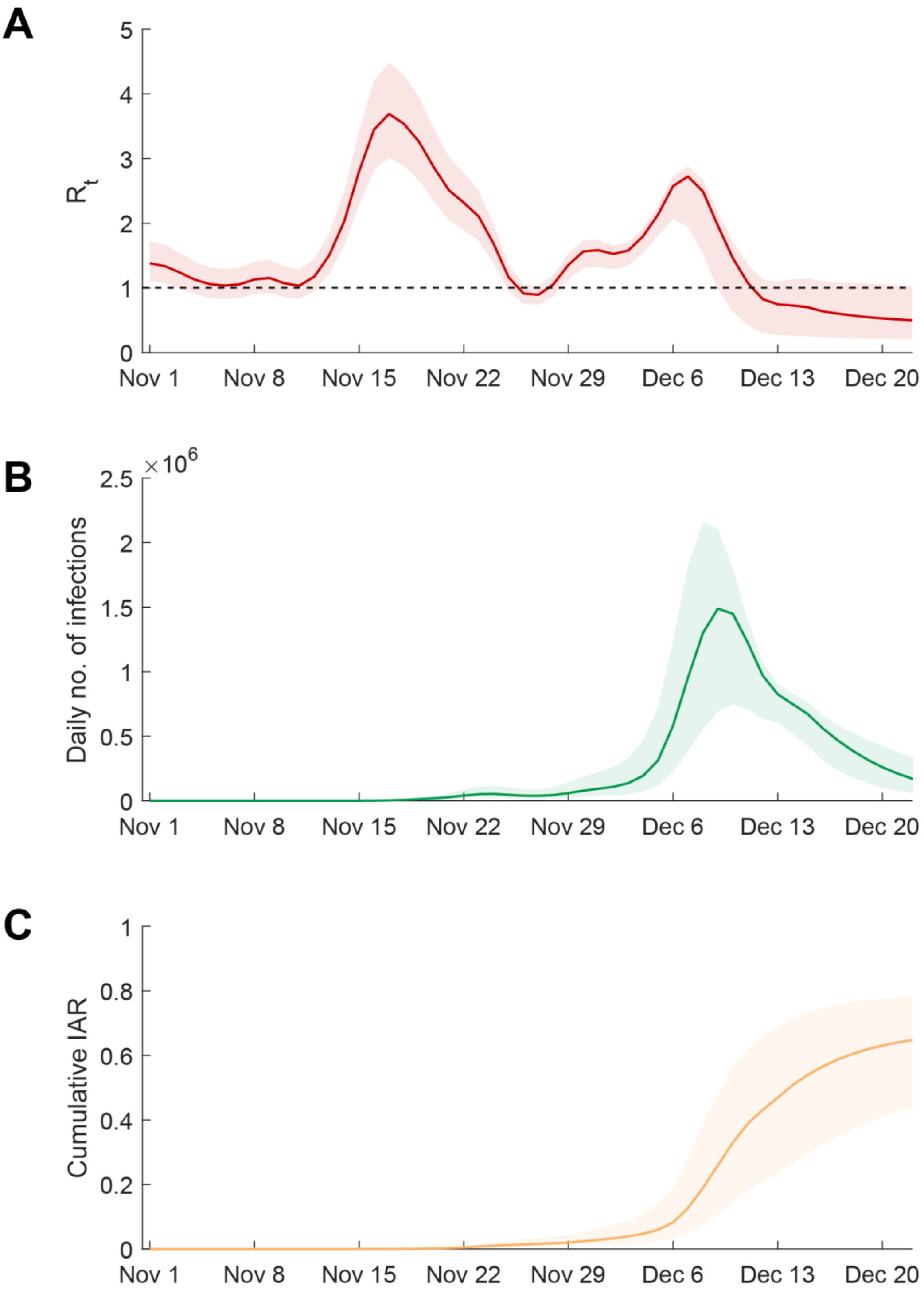
* Data from https://weibo.com/u/2125939111 and https://www.mtr.bj.cn/

Supplementary Table 3. Parameters fitted in the transmission model

Parameter	**Description**	**Estimate (95% CrI)**
γ_1	The scaling factor for translating the mobility data proxy into the contact matrix between November 1 and 11 (see methods)	0.028 (0.026 – 0.031)
γ_2	The scaling factor for translating the mobility data proxy into the contact matrix after November 25 (see methods)	0.092 (0.090 – 0.094)
M	The number of local infections on November 1 that might generate community transmission when the simulation was started	311 (133 – 645)
p_{report}	The proportion of infections ascertained as symptomatic cases by Beijing Municipal Health Commission	0.34 (0.23 – 0.49)

Supplementary Table 4. Fixed parameters in the transmission model

Parameter	**Description, assumption, and source**	**Value**
T_{GT}	Mean generation time [8]	4.6 days
f_{GT}	Probability density function of generation time [8]	Gamma (2.20, 2.09)
VE_S	Vaccine effectiveness in reducing susceptibility	Assumed to be 0 since most of the vaccinations were given >8 months ago and most of the vaccines were inactivated virus vaccines
VE_I	Vaccine effectiveness in reducing infectiousness	Assumed to be 0
$f_{incubation}$	Probability density function of incubation period [17,18]	Gamma distribution Mean: 3.5 days SD: 2.6 days



Supplementary Figure 1. Estimated R_t, daily incidence and cumulative infection attack rate in Beijing, assuming ascertainment probability was 80% after November 11. **(A)** Estimated R_t between November 1 and December 21. The R_t between December 15 and 21 were estimated assuming that the Beijing MTR mobility and population mixing level (and hence R_t) would remain at the same levels of December 14 for the next 7 days. **(B)** Estimated daily number of infections between November 1 and December 21. **(C)** Estimated cumulative infection attack rates between November 1 and December 21. Lines indicate the mean of estimates and shades indicate the 95% credible interval (95% CrI).

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