S1 Description of Simulator

S1.1 General description of data structure and behavior

The simulator developed for the present work is designed to study how an infectious disease spreads in a single urban area. We begin the description of the simulator by viewing the single data structure, which holds all the information for the simulation. We denote the single instance of the structure by \textit{city} and similarly use bold Roman letters to refer to any items in the computer. The simulated urban area consists of towns and railway lines connecting them, and each town consists of \textit{places} and residents. The structure of the places has fields for the type of place, the transmissibility parameter $\beta$, the numbers of people in various health states who visit, and the transition probabilities between health states. The possible types of places are \textit{corporation}, \textit{school}, \textit{shop}, \textit{park}, \textit{home}, and \textit{train}. Users can characterize the type of places by properly configuring the value of $\beta$. A resident has fields for role, health state, place currently visiting, candidates for places to be visited, and a schedule. The health status is defined as conforming to the SEIR macro simulation model\textsuperscript{12}. There are four possible states: $s$ means the individual is susceptible to the virus, $e$ means the individual is infected without being contagious, $i$ means the individual is infected and contagious, and $r$ means the individual is either recovered and immune or dead. Individuals can have the role of \textit{employee}, \textit{student}, or \textit{domiciliary}. The simulator is equipped with predefined schedules for each of the roles (the behaviors for each role will be described below). At the scheduled time, the location of each individual is changed instantaneously if the move takes place inside the currently visited town, but if transportation by train is required, the individual remains in place until a train arrives or remains on the train until the journey is completed.

The components mentioned above are combined to form a single step of the simulator shown in Fig. S1. This procedure processes each person in each town. Since determining the movement and the health status for each individual can be performed independently, these operations are carried out in parallel, although the update of the transition probabilities should be atomic (the operations marked with a star in Fig. S1); that is, consecutive operations assigned to a process element are performed, and the rest of the process elements must pause until the operations are completed.

S1.2 Infectious transmission

A single step of the simulation is carried out by updating the currently visited location and the health status of each individual. First, we consider simulations without vaccination. Suppose that the simulator is currently processing an individual who visits a location where the numbers of visitors in total and in state $i$ are $N$ and $I$, respectively, and the transmissibility parameter is $\beta$. Then, the transmission and
do area ∈ city.areas
!$omp do
do person ∈ area.persons,
    following to person.schedule, change person.visit.
    if person.visit changes from v to v' (v ≠ v') then
        let h = person.visit
        !$omp critical
        decrement area.places(key=v).nVisitors[key=h].
        recalculate area.places(key=v).pr.
        Increment area.places(key=v').nVisitors[key=h].
        recalculate area.places(key=v').pr.
        !$omp end critical
end if
change person.health according to probability area.places(key=v).pr.
if person.health changes from h to h' then
    let v = person.visit
    !$omp critical
    decrement area.places(key=v).nVisitors[key=h].
    Increment area.places(key=v).nVisitors[key=h'].
    recalculate area.places(key=v).pr.
    !$omp end critical
end if
end do
!$omp end do
end do

Figure S1: Pseudo code of a single step of the simulation. All information on the simulated urban area is contained in the structure instance city, which is located in shared memory. Iterations and branches are in a Fortran-like code, but the structure name and its field are split by a dot. Simulations are carried out in parallel based on OpenMP, and iterations marked by !$OMP DO are adequately split by the compiler and carried out in parallel. Calculation of the transition probability places[key=v].pr is implemented to conform to the diagram of Eq. (2).
progress of the disease are simulated through a stochastic update of the health status of this individual
with probabilities given by the diagram,
\[ s \xrightarrow{\beta I/N} e \xrightarrow{\alpha} i \xrightarrow{\gamma} r, \]
where the formula accompanying an arrow expresses the transition probability per unit time from the
source to the destination. This definition of transition probabilities realizes the variation in the number
of people in each state during an infinitesimal time so that the expectation among stochastic variants
agrees with the variation of the corresponding variable in the SEIR model.

Simulations with vaccinated people require more states and modifications in the transition probabil-
ities. We thus add state \( v \) to the possible health states and give probability \( \mu \) and hyposensitization
parameter \( \nu \in [0,1) \) to the vaccinated people. With the new state \( v \) and parameters \( \mu \) and \( \nu \), the
transition probabilities are modified as
\[
\begin{align*}
\frac{s}{\beta I/N} & \xrightarrow{e} \frac{\alpha}{i} \xrightarrow{\gamma} r, \\
\frac{\mu \delta(t-t_{vac})}{s'} & \xrightarrow{\beta I/N} e \xrightarrow{\alpha} i, \\
\frac{\eta}{s''} & \xrightarrow{\beta I/N} e \xrightarrow{\alpha} i', \\
\frac{\gamma/v}{r} & \xrightarrow{s''} i', \\
\end{align*}
\]
The primed states have a meaning similar to that of their unprimed version, but the transition prob-
abilities are modified due to the effect of the vaccine. For the susceptible state, two additional states
\( s'' \) and \( s' \) exist. Both states mean that a vaccine has been administered; the vaccine is not active in \( s'' \)
but is active in \( s \). The vaccine provided may or may not match the actual virus, depending on both the
vaccine design and the individual’s immune system. To describe this in the simulator, we decided with
probability \( \nu \) that the dosed vaccine protects the target person. The inverse of the transition probability
from \( s'' \) to \( s' \) is the latent period of activation. The transition from \( s' \) to \( i' \) is less probable than is that
from \( s \) to \( i \). This means that the activated vaccine protects a person from being infected by contagious
people. The transition from \( i \) to \( r \), in turn, is more probable, which reflects that the infectious period is
shortened by the vaccine.

**S1.3 Enhancement of transmissibility in crowded trains**

Trains are different from other places in that the transmissibility may change a great deal due to the
number of passengers in the train cars. To incorporate this in our model, we first estimated the mean dis-
tance between passengers from the number of passengers in cars, and then calculated the transmissibility
as a function of the mean distance.

In typical train cars, the floor area is approximately 60 m\(^2\) (\( \approx \) width 2950 mm \( \times \) length 200,000
mm), and the standard capacity is approximately 150 people. Based on these parameters, we related the
occupancy \( \sigma \) to the mean distance \( D \) as
\[
D/[m] = \sqrt{\frac{60}{150\sigma}} \approx 0.63/\sqrt{\sigma}.
\]
We obtained the maximum number of passengers in one train car by presimulation and noted this number
was twice the standard capacity (\( \sigma = 2 \)). The reason we did not calculate the mean distance directly from
the number of passengers was to enable the scaling of the city population without changing the frequency
of the train service. Transmissibility significantly increases if $D$ becomes smaller than a critical value $D_0$. We modelled this by assuming that the reproduction number $R$ in a train follows a Yukawa-type potential,

$$R(D) = R_0 \exp(-D/D_0),$$

where $D_0 = 3m$ are used and values of baseline $R_0$ are used in Table 2 of the main text for the description of the reproduction number of trains.

### S1.4 Scheduling

The schedules of individual people are decided at midnight every day by the schedule generators prepared for the respective roles.

**Employee** The mandatory tasks on weekdays are a trip from home to the corporation and a return trip. The scheduler randomly chooses from 6:00–10:00 for the former and from 18:00–22:00 for the latter. Additionally, employees may visit other corporations. If employees have two or more corporations as candidate visiting places, then the generator takes some or all of them and assigns visiting times from 10:00–16:00 and visiting durations from 30 min–2 hours. On days off (Saturday and Sunday), schedules are configured so that employees randomly wander their candidate visiting places.

**Student** Student schedules are similar to those of employees. However, the trip to school begins from 6:00–8:00 and the return trip is from 16:00–19:00. Some students return to school in the evening, going there from 19:00–20:00 and returning from 21:00–22:00.

**Domiciliary** This role includes preschool children and retired people. Domiciliaries’ visiting places include at least one supermarket located in the town in which they live, and optionally other supermarkets and parks, which may be outside their home town. Domiciliaries are scheduled to visit a supermarket for 1 hour during 10:00–20:00 as a mandatory task, and optionally to visit other candidate places following the same rule.

### S2 Configuration of the simulator in the present study

#### S2.1 Model city

We employed a model urban area for which the number of residents and places are given in Table S1. This model is based on the five towns along an arterial railway line (Chuo Line) going east and west in the city of Tokyo. We used the actual population by 5-year age groups, as provided by the Tokyo metropolitan government for 2005. The distribution is shown in Fig. S2. We sampled from this distribution and then assigned roles according to the following rules: (a) All individuals aged $\leq 22$ are students, (b) 70% of the individuals in the range $22 < \text{age} \leq 60$ are employees, and (c) the remaining 30% of the individuals in the range $22 < \text{age} \leq 60$ and all individuals with age $> 60$ are domiciliaries. Homes were constructed by randomly combining several people chosen from the population constructed from these statistics. The number of schools in each town was also taken from these statistics. The number of corporations, however, was arbitrarily chosen so that they were concentrated at the central towns D and E and the scale of the corporations follows a Pareto distribution.

To construct corporations that follow a Pareto distribution, we began by randomly assigning employees to corporations. Suppose that $N$ corporations follow a (truncated) Pareto distribution. Then, the number
Figure S2: Age-specific distribution of the population of Tokyo in 2005. We sampled from this distribution to obtain the ages of individuals, and their roles were assigned according to their ages. The proportions of roles in the simulation are represented by different colors (blue: students, red: employees, and yellow: domiciliaries).

of corporations, whose scale factor for the number of employees is between $x$ and $x + dx$, is proportional to

$$q(x) = \frac{\beta \alpha^\beta}{x^{\beta+1}} \quad (\alpha \leq x \leq \gamma),$$

where the lower and the upper limits of the scale factors $\alpha$ and $\gamma$ are chosen later. The cumulative $Q(x)$ is given by

$$Q(x) = \int_{\alpha}^{x} q(x)dx \quad (\alpha \leq x \leq \gamma).$$

Some discretization is necessary to actually construct a corporation. To do this, we took the scale factor $x_y$ of the $y$-th ($y = 1, \cdots, N$) corporation from the smallest one, such that

$$\int_{x_{y-1}}^{x_y} q(x)dx = \frac{1}{N} Q(\gamma), \quad \text{or equivalently,} \quad \int_{x_0}^{x_y} q(x)dx = Q(x_y) = \frac{y}{N} Q(\gamma), \quad (4)$$

where $x_0 \equiv \alpha$ and $x_N \equiv \gamma$. Then, we can construct corporations by randomly drawing the index of the corporation, $y$, with the probability $p(y)$ proportional to $x_y$, and assigning a person to corporation $y$, where we have

$$p(y) \propto x_y = Q^{-1}\left(\frac{y}{N} Q(\gamma)\right) \quad (0 < y \leq N).$$

The inverse transform sampling enables us to sample $y$, that is, $y \sim p(y)$ if we set $u \sim U[0, 1)$, $P(y) = \int_{0}^{y} p(y')dy'$ and $y = P^{-1}(u)$. The actual form for transforming $u$ to $y$ is

$$y = N \left[ 1 - \left(1 - (\beta - 1) \frac{uP_1}{\alpha \beta} \right)^{\frac{1}{\beta-1}} \right]/\left[1 - \left(\frac{\alpha}{\gamma}\right)^\beta\right] \quad \text{with} \quad P_1 = \frac{\alpha \beta}{\beta - 1} \left[1 - \left(\frac{\alpha}{\gamma}\right)^{\beta-1}\right]. \quad (5)$$

The size distribution of the 2,000 corporations obtained in the simulations is shown in Fig. S3. The largest corporation had 2,306 employees and the smallest had 30.
S2.2 Transmissibility and progress of disease

The magnitude and the differences in the transmissibility of disease among the different types of locations are controversial. In the above discussion, we assigned the transmissibility of disease in terms of the reproduction number for location types as follows: corporations (3.0), schools (3.6), hospitals (2.4), homes (2.4), parks (1.0), and shops (0.6).

The parameters $\alpha$ and $\gamma$ give the inverses of the mean latent and the mean infectious periods, respectively. We set $\alpha^{-1} = 3.5$ days and $\gamma^{-1} = 3$ days. The entire illness period $\alpha^{-1} + \gamma^{-1} = 6.5$ days is reasonable as a representative value for influenza. These values ultimately determine the timescale for the spread of influenza, and the fact that the peak occurs at around the 75-th day in the unvaccinated case also supports this selection.

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Table S1: List of parameters configuring simulation

- Mean latent period: $\alpha^{-1} = 3.5$ days
- Mean infectious period: $\gamma^{-1} = 3.0$ days
- Reproduction number $R$ of each place kind

| place | train | school | workplace | household | park | shop | AR |
|-------|-------|--------|-----------|-----------|------|------|----|
| case A | 1.5   | 2.0    | 2.0       | 2.0       | 1.0  | 0.6  | 0.30 |
| case B | 1.0   | 2.5    | 2.5       | 2.0       | 1.0  | 0.6  | 0.29 |
| case C | 1.0   | 2.0    | 2.0       | 4.0       | 1.0  | 0.6  | 0.28 |

Note: reproduction number $\gamma R$ is related to transmission efficiency $\beta$, where $\beta = \dot{S}/SI$ with the numbers of susceptible $S$ and infectious $I$ persons.

- Places and Population in the model city

| town | school | workplace | park | population | shop |
|------|--------|-----------|------|------------|------|
| A    | 70     | 100       | 2    | 571,641    | 100  |
| B    | 20     | 100       | 2    | 176,866    | 100  |
| C    | 12     | 100       | 2    | 138,684    | 100  |
| D    | 29     | 2000      | 2    | 314,861    | 100  |
| E    | 8      | 2000      | 2    | 44,680     | 100  |

- The number of initial infected people: 600

- Distribution of corporation sizes
  Shown in Fig. S3. Parameters of Pareto distribution are $\alpha = 1$, $\beta = 2$, $\gamma = 100$. 

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