Disparities in Spread and Control of Influenza in Slums of Delhi: Findings From An Agent-Based Modeling Study

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Presentation of Results.

For each set of input parameters, 25 replicates were run using agent-based simulation and the results presented are the average values over the 25 replicates. Also, 95% confidence intervals (CIs) are given when appropriate.

Comparisons Between Network 1 and Network 2.

Table S1 shows some differences between network1 and network 2 due to their different ways of modeling slum population. Note that these two networks are the same ones as those used in Chen et al.[1]. Further comparisons between the two networks are found in Chen et al.[2].

Table S1. Comparison of two networks as well as data sources for slum and non-slum Delhi, India.

	Network 1		Network 2	
	Slum	Non-slum	Slum	Non-slum
Population Size	0	13.8 million	1.8 million	12 million
Average Household Size of Slum Region	5.2		15.5	
Daily Activities	33,890,156		39,077,861	
Number of Edges	210,428,521		231,258,772	
Average Degree	30.4		33.4	
Maximum Degree	170		180	
Data Sources	MapMyIndia.com		MapMyIndia.com Indiamart.com MapMechanic.com	

Network 2 contains 298 slum zones, while network 1 models the whole population as non-slum. For network 1, the non-slum demographics and activities data is collected by survey through MapMyIndia.com. While for slum population, we collected additional data by Indiamart.com and MapMechanic.com for slum demographics and activities as well as slum polygons. More detailed demographic and activity differences can be found in the Chen et al.[1]

Terminology and Abbreviations for Interventions.

Table S2 contains abbreviations for different interventions and their meanings. Stay-at-home (SHO) and social isolation (ISO) interventions are applied to a person immediately after they become infected, while close-schools (CS) and vaccinations (VAX) may be applied after a specified fraction of the total population has been infected.

Table S2: Summary of abbreviations for interventions and their meanings.

Abbreviation	Definition
CS	Close-schools: School-related interactions are eliminated.
CSx	Close-schools is implemented after the total fraction of the population that has been infected reaches x.
ISO	Social isolation: a person who is socially isolated does not interact with any other person, even people in their home. Isolation is triggered only after a person becomes infectious.
SHO	Stay at home: All out-of-the-home activities for this person are eliminated, and this person only interacts with others at home. Stay at home is triggered only after a person becomes infectious.
VAX	Vaccination: a person who is vaccinated has a reduced probability of contracting the virus.
VAXx	Vaccination of an individual occurs after the total fraction of the population that has been infected reaches x.

Table S3 contains the variables used in simulations. The transmissibility corresponds to strong flu in Chen et al.[1] For vaccination, efficacy is either 30% or 70%. That is, for 30% efficacy, a person who gets vaccinated has reduced their susceptibility to infection by 30%.

Table S3: Summary of parameters and values used in simulations.

Category	Values
Networks of Delhi	Network 1 (does not model slums); Network 2 (models slums).
Seeding	20 people selected randomly over the entire population at time 0 as index cases.
Transmissibility	0.000027.
Intervention approaches.	Base case (no intervention); close-schools (CS); stay-home (SHO); isolation (ISO); vaccination (VAX).
Intervention/compliance rates.	10%, 30%, 50%, 70%, 90%.
Efficacy of vaccination intervention.	30%, 70%.
Intervention trigger time	Cumulative infection rate reaches 0%, 1% and 5%.
Simulation replicates	25

The Agent Epidemic States and Disease Model.

An SEIR, Susceptible (S), Exposed (E), Infectious (I) and Removed or Recovered (R) model is considered within each individual. An infectious person spreads the disease to each susceptible neighbor independently with a probability referred to as the transmission probability, given by

$$p = \lambda\,(1 - (1 - \tau)^{\Delta t}),$$

where λ is a scaling factor to lower the probability (e.g., in the case of vaccination), τ is the transmissibility and Δt is the duration of interaction in minutes. Durations of contact are labels on the network edges. A susceptible person undergoes independent trials from all of its neighbors that are infectious. The transmission probability is a function of the number and duration of contacts.[3] This is selected to simulate an Influenza model resulting in a R_0=1.26 (cumulative attack rate 42%, corresponding to a transmissibility of 0.000027 per minute of contact time) for Network 1, and R_0=1.39 (cumulative attack rate 48%) for Network 2.[4] This transmissibility value is used uniformly throughout this study and corresponds to the probability at which an infectious node infects a susceptible node per minute of contact.

At each time (day), if an infectious person infects a susceptible person, the susceptible person transitions to the exposed (or incubating) state. The exposed person has contracted Influenza but cannot yet spread it to others. The incubation period is assigned per person, according to the following distribution: 1 day (30%); 2 days (50%); 3 days (20%). At the end of the exposed or incubation period, the person switches to an infected state. The duration of infectiousness is assigned per person, according to the distribution: 3 days (30%); 4 days (40%); 5 days (20%); 6 days (10%). After the infectious period, the person recovers and stays healthy for the simulation period. This sequence of state transitions is irreversible and is the only possible disease progression.

Epidemic Curves for Other Interventions, for Varying Efficacy and Compliances.

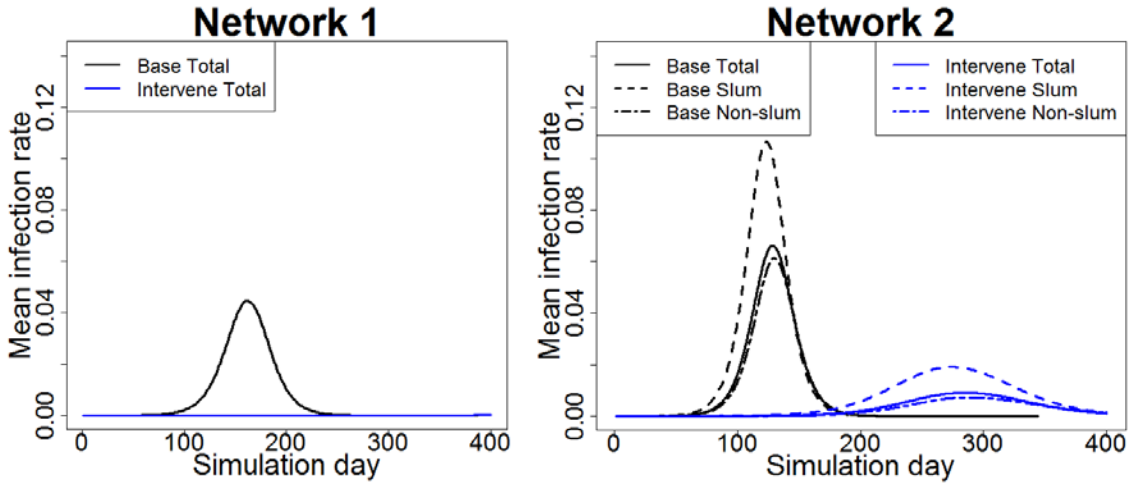


Figure S1: Epidemic curves for the base case and the vaccination case. The vaccines are given randomly to 50% of the entire population, and the vaccine efficacy is assumed to be 30%. The transmissibility is 0.000027.

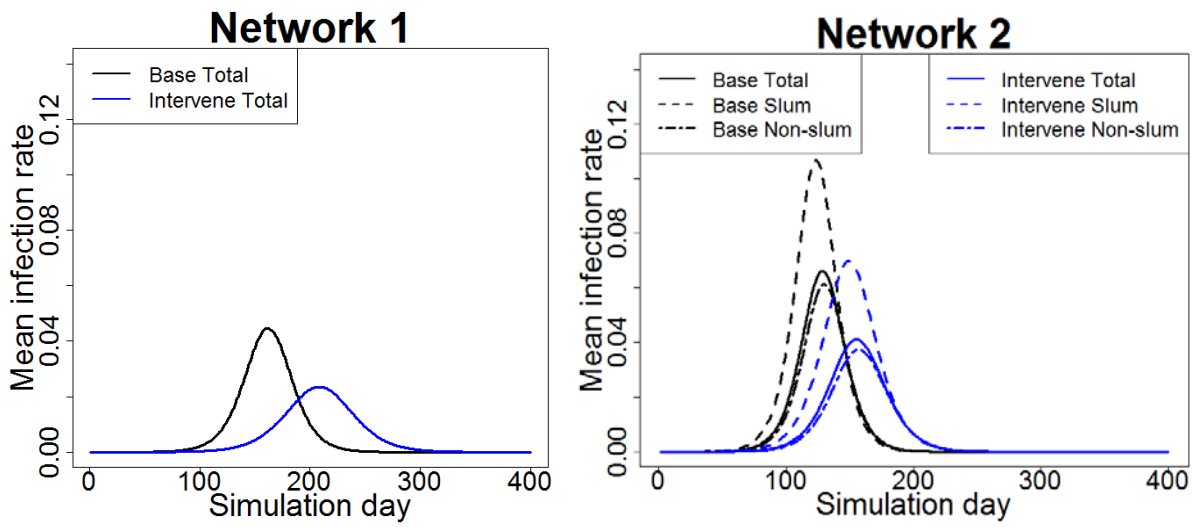
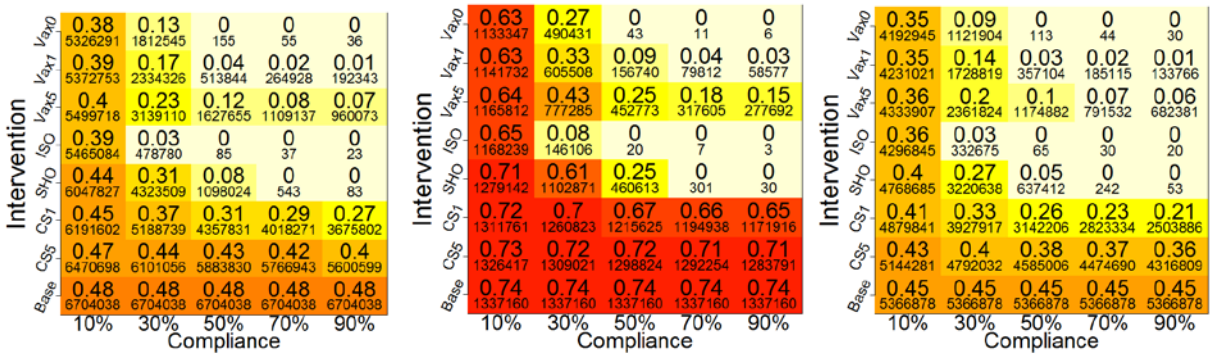


Figure S2: Epidemic curves for the base case and vaccination case. The vaccines are given randomly to 10% of the entire population and the vaccine efficacy is 70%. The transmissibility is 0.000027.



(a) Total Delhi (b) Slum (c) Non-slum

Figure S3. Heat map of mean cumulative infection rates in Delhi, and slum and non-slum regions under different intervention strategies for Network 2. The vaccination efficacy is fixed at 70%. Five different compliance rates, i.e., 10%, 30%, 50%, 70% and 90% and 4 types of intervention strategies, i.e. vaccination (VAX), close-schools (CS), stay-home (SHO) and isolation (ISO), are considered. For vaccines, three different trigger points are considered: when cumulative infection rate reaches 0% (VAX0), 1% (VAX1) and 5% (VAX5). For close-schools, two trigger points are used i.e. when cumulative infection rate reaches 1% (CS1) and 5% (CS5). Compliant individuals are selected randomly from the entire Delhi population and the mean cumulative infection rates are calculated separately for the total population, and slum and non-slum subpopulations. Base is the baseline case with no interventions. The smaller-font numbers under the infection rate show the actual number of infected individuals. Darker colors correspond to higher infection rates.

Tabulations of Basic Results: Comparisons between Networks 1 and 2 for Compliance of 30% and Efficacy of 30%.

Table S4 shows results when 30% of the population that is selected uniformly at random is vaccinated with a vaccine that is 30% effective. The contrast between the two populations is even greater when considering interventions. The peak infection rate of the entire population increases by 123.2% (95% CI: 122.7%-123.7%) in Network 2 compared to Network 1 for the intervention, versus 47.6% difference between the networks in Table S8. The time to peak decreases by 35.7% (95% CI: 32.9%-38.8%) in Network 2 compared to that in Network 1, for the intervention case, compared to only 20.84% percentage change between the two Networks for the base case in Table S8. The cumulative infection rate (or attack rate) is also underestimated, which is 42.2% (95% CI: 41.5%-42.8%) greater on average in Network 2 compared to Network 1 for the intervention case. Hence, the differences between key epidemic results for Networks 1 and 2 that are generated for the intervention case are even more pronounced than they are for the base case. These values are all statistically significant.

Table S4: Comparisons of key epidemic parameters for Networks 1 and 2 for a vaccination intervention before the epidemic starts (VAX0), where the vaccine efficacy is 30% and the compliance rate is 30%.

Vaccination	Network 1	Network 2	Compare-absolute	Compare-relative
Time to Peak	286	184	102 (95% CI: 94-111)	35.7% (95% CI: 32.9%-38.8%)
Peak Infection Rate	1.34%	2.99%	1.65% (95% CI: 1.64%-1.66%)	123.19% (95% CI: 122.69%-123.65%)
Cumulative Infection Rate	23.3%	33.1%	9.82% (95% CI: 9.67%-9.96%)	42.17% (95% CI: 41.51%-42.77%)

Table S5 shows the effect of delay in applying interventions. The numbers show the percentage difference in cumulative infection rate in slums and non-slums of Network 2 for the specified interventions and compliance rates at different trigger levels. For example, the value 30.55% at 0.1% compliance means that for intervention close-schools, where this intervention is implemented after 5% of the total population is infected, the fraction of people in slums that get infected is 30.55% greater than the fraction of non-slum residents who get infected.

Table S5. Differences of epidemic size between slum and non-slum regions for Network 2 for base case (no intervention); close-schools (CS) after 1% total outbreak fraction (CS1) and after 5% total outbreak fraction (CS5); stay at home (SHO); social isolation (ISO); vaccination (VAX) after 1% total outbreak fraction (VAX1) and after 5% total outbreak fraction (VAX5), under various compliance rates. The vaccination efficacy is 30%.

Compliance	Base	CS5	CS1	SHO	ISO	VAX5	VAX1
0.1	29.30%	30.55%	31.94%	31.06%	28.85%	29.37%	29.27%
0.3	29.30%	32.52%	37.03%	34.18%	5.31%	28.85%	28.21%

0.5	29.30%	33.67%	41.07%	20.16%	0.00%	26.72%	24.62%
0.7	29.30%	34.23%	42.57%	0.01%	0.00%	21.94%	15.87%
0.9	29.30%	35.07%	43.95%	0.00%	0.00%	18.31%	7.25%

Table S6 examines the difference in effects of interventions on the cumulative infection rate in Network 2. These data use both the stay home (SHO) and the isolation (ISO) interventions as base cases. Each entry represents the difference between the cumulative infection rates for the specified pharmaceutical interventions and SHO or ISO. For example, 18.03% means that the cumulative infection rate for vaccinating after 5% of the population is infected, is 18.03% greater than that for the intervention of SHO; 31.92% means that the cumulative infection rate for vaccinating after 5% of the population is infected is 31.92% greater than that for the intervention of ISO. Thus, the larger the magnitude of a positive number, the greater the effectiveness of SHO or ISO compared to the specified pharmaceutical intervention.

Table S6. Differences in epidemic size between stay at home (SHO) interventions, social isolation (ISO) interventions and pharmaceutical interventions (VAX0, VAX1, VAX5), under various compliance rates. The compliance rate and efficacy for vaccination is 30% and 30%, respectively.

Compliance	Vax5-SHO	Vax1-SHO	Vax0-SHO	VAX5-ISO	VAX1-ISO	VAX0-ISO
0.1	0.71%	0.29%	0.17%	4.92%	4.49%	4.38%
0.3	4.15%	2.39%	1.89%	31.92%	30.17%	29.66%
0.5	18.03%	13.51%	11.35%	25.96%	21.44%	19.28%
0.7	16.82%	9.75%	0.13%	16.82%	9.76%	0.13%
0.9	13.13%	4.01%	0.00%	13.13%	4.01%	0.00%

Effect of intervention on Network 2, With and Without Interventions.

The comparison between vaccination intervention and the base case in Network 2 is detailed in Table S7 below.

In Network 2, for the total population, vaccination delays the time to peak infection by 43.27% (95% CI: 40.14%-46.41%) relatively, from 128 to 184 days on average, while the peak infection rate is reduced by about 3.88% from 2.99% to 6.87% on average (56.47% relatively with 95% CI: 56.35%-56.56%). The total infection rate is reduced by 15.31% from 33.12% to 48.43% (31.62% relatively with 95% CI: 31.57%-31.67%).

In slum regions in Network 2, vaccination delays the time to peak infection by 43.09% (95% CI: 39.78%-46.4%) relatively, from 123 to 176 days on average, while the peak infection rate is reduced by about 5.70% from 5.42% to 11.12% on average (51.26% relatively with 95% CI: 50.88%-51.64%). The total infection rate in slums is reduced by 16.35% from 57.53% to 73.88% (22.13% relatively with 95% CI: 22.07% to 22.19%).

In non-slum regions in Network 2, the time to peak is delayed by 43.44% (95% CI: 40.32%-46.56%) relatively, from 130 to 186 days on average, while the peak infection rate is reduced by about 3.68% from 2.69% to 6.36% on average (57.79% relatively with 95% CI: 57.64%-57.94%). The total infection rate in non-slums is reduced by 15.16% from 44.60% to 29.45% (33.98% relatively with 95% CI: 33.93% -34.03%).

Table S7: Comparisons between the base and vaccination cases for Network 2. The three parameters (time to peak, peak infection rate and cumulative infection rate) are broken out, and for each, values for the total population, and slum and non-slum subpopulations are given. The vaccination rate is 30% and efficacy is 30% for those receiving the vaccine.

Network 2, Time to Peak	Base	Vaccination	Compare-absolute	Compare-Relative
Total	128	184	55 (95% CI: 51-59)	43.27% (95% CI: 40.14%-46.41%)
Slum	123	176	53 (95% CI: 49-57)	43.09% (95% CI: 39.78%-46.4%)
Non-Slum	130	186	56 (95% CI: 52-60)	43.44% (95% CI: 40.32% - 46.56%)

Network 2, Peak Infection Rate	Base	Vaccination	Compare-absolute	Compare-Relative
Total	6.87%	2.99%	-3.88% (95% CI: -3.870% -3.884%)	-56.46% (95% CI: -56.35% -56.56%)
Slum	11.12%	5.42%	-5.70% (95% CI: -5.66% -5.74%)	-51.26% (95% CI: -50.88% -51.64%)
Non-Slum	6.36%	2.69%	-3.68% (95% CI: -3.67% -3.69%)	-57.79% (95% CI: -57.64% -57.94%)

Network 2, Cumulative Infection Rate	Base	Vaccination	Compare-absolute	Compare-Relative
Total	48.43%	33.12%	-15.31% (95% CI: -15.29% -15.34%)	-31.62% (95% CI: -31.57% -31.67%)
Slum	73.88%	57.53%	-16.35% (95% CI: -16.30% -16.39%)	-22.13% (95% CI: -22.07% -22.19%)
Non-Slum	44.60%	29.45%	-15.16% 95% CI: (-15.14% -15.18%)	-33.98% (95% CI: -33.93% -34.03%)

Table S8 summarizes differences in key epidemic parameters for Networks 1 and 2 for the base case with no interventions. The peak infection rate is the maximum fraction of individuals who are infected on any day, the time to peak is the day on which the peak infection rate occurs, and cumulative infection rate is the cumulative fraction of individuals who get infected in the epidemic. Under the base case, the peak infection rate in Network 2 is 47.6% (95% CI: 47.4%-47.8%) greater compared to that in Network 1 (47.6%=(6.87%-4.65%)/4.65%). The time to peak infection for Network 2 is decreased by 20.8% (95% CI: 19.2%-22.7%) compared to that in Network 1. The cumulative infection rate (or attack rate) is also underestimated under Network 1 by 16.1% (95% CI: 16.1%-16.2%) compared to Network 2. These results, presented in the main paper, are tabulated here in Table S8 for convenience and comparison.

Table S8: Comparisons of key epidemic parameters for Networks 1 and 2 for the base case.

Base	Network 1	Network 2	Compare-absolute	Compare-relative
Time to Peak	162	128	34 (95% CI: 31-37)	20.84% (95% CI: 19.19%-22.71%)
Peak Infection Rate	4.65%	6.87%	2.215% (95% CI: 2.206%-2.224%)	47.6% (95% CI: 47.4%-47.8%)
Cumulative Infection Rate	41.70%	48.43%	6.73% (95% CI: 6.71%-6.75%)	16.1% (95% CI: 16.1%-16.2%)

Effect of intervention on Network 1, With and Without Interventions.

In Network 1, vaccination delays the time to peak infection by 76.41%, from 162 to 286 days on average, with 95% CI: 71.53%-81.28%. The peak infection rate is reduced by 3.3121 percentage points, from 1.34% to 4.65%, which is a relative percentage difference (RPD) of -71.20%, with 95% CI: -71.02% to -71.38%. These and cumulative infection rate data are given in Table S9.

Table S9: Comparisons of a vaccination intervention (30% vaccination rate, 30% efficacy of a vaccination) with the base case in Network 1 Delhi.

Network 1,Total	Base	Vaccination	Compare-absolute	Compare-relative
Time to Peak	162	286	124 (95% CI: 116-132)	76.41% (95% CI: 71.53%-81.28%)
Peak Infection Rate	4.65%	1.34%	3.31% (95% CI: 3.30%-3.32%)	71.20% (95% CI: 71.02%-71.38)
Cumulative Infection Rate	41.7%	23.3%	18.40% (95% CI: 18.25%-18.55%)	44.13% (95% CI: 43.77%-44.48%)

Tables S7 and S9 show that, generally, Network 1 is more responsive to intervention than Network 2. In Network 1, the percentage changes in time-to-peak, peak infection rate, and cumulative infection rate, due to intervention, are 76.4%, -71.2%, and -44.1%,

respectively. For Network 2, these values are 43.3%, -56.5%, and -31.6%, respectively. The reason for lower impact in Network 2 is the greater connectivity of households in slums, which helps drive the contagion.

Effect of interventions on slum and non-slum subpopulations of Network 2, compared to the base case.

The data used in comparing key outbreak parameters in slum and non-slum regions are taken from Table S7, and the corresponding epidemic curves are in Figure 1. The percentage change in peak infection rate due to intervention in slum (-51.3%) and non-slum (-57.8%) regions in Network 2, are comparable, although the magnitudes of the peak infections in slums are about twice those in the non-slum regions. For the cumulative infection rates, the relative drop from the intervention is greater for the non-slum (-34.0% vs. -22.1%) population than it is for the slum population, but the absolute drop is about the same (-16.3% vs. -15.1%).

Table S10: Comparison of results between slum and non-slum in Network 2. The input data is the same as in Table S7.

Network 2, **Base**	Slum	Nonslum	Compare-absolute	Compare-relative
Time to Peak	123	130	7(95% CI: 4-9)	5.26% (95% CI: 3.37%-7.16%)
Peak Infection Rate	1.12%	6.36%	4.76% (95% CI: 4.72%-4.80%)	42.79% (95% CI: 42.46%-43.14%)
Cumulative infection rate	73.88%	44.60%	29.25% (95% CI: 29.25% - 29.31%)	39.63% (95% CI: 39.59%-39.67%)

Network 2, **Vaccination**	Slum	Nonslum	Compare-absolute	Compare-relative
Time to Peak	176	186	10(95% CI: 5-15)	5.23% (95% CI: 2.58%-8.46%)
Peak Infection Rate	5.42%	2.69%	2.74% (95% CI: 2.71% - 2.76%)	50.46% (95% CI: 50.06%-50.86%)
Cumulative infection rate	57.53%	29.45%	28.08% (95% CI: 28.04%-28.12%)	48.82% (95% CI: 48.74%-48.89%)

Figure S4 contains the percentage changes between the base case and intervention case for Networks 1 and 2 for the three parameters in the legend, and further breaks down Network 2 into slum and non-slum subpopulations. This plot provides a summary of differences between the base and intervention cases. For all four conditions considered, the intervention reduces the severity of an epidemic. It delays the time when the infection peaks, and reduces the peak infection and the cumulative infection rates. Note that the intervention has a larger effect on the epidemics when applied to Network 1, as consistent with Figure 1.

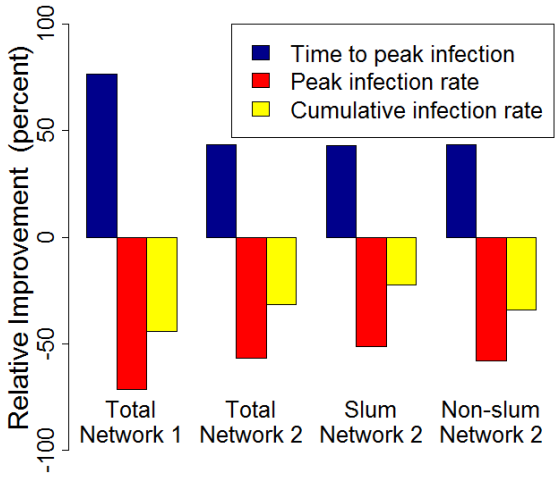


Figure S4: Effects of vaccination on time to peak infection, peak infection rate, and cumulative infection rate. The intervention is 30% vaccination rate and 30% vaccine efficacy. Each bar refers to the average value of the relative difference over 25 runs. Vaccination is more effective for Network 1 than Network 2, while, for Network 2, it is slightly more effective for the non-slum population than slum. Details of the data associated with this plot are provided in Tables S7 and S9.

Figure S5 provides the same data in as in Figure S7, but now the data are provided as absolute differences, rather than as percentage changes. (There are three separate plots owing to the different ranges in absolute differences. Qualitatively, the time to peak infection (blue bars) does not change between the two networks and the two subpopulations of Network 2 (Figure S4 versus Figure S5(a)). However, the red bars in Figure S4 are qualitatively different from those in Figure S5(b), when considering absolute changes. That is, the magnitude of the percentage change in peak infection rate between the base and intervention cases is greatest in Network 1 (Figure S4, red bars), while in Figure S5(b), it is least on an absolute change basis. Similarly, the slum population in Network 2 shows the least percentage change in Figure S4, but the greatest absolute change in Figure S5(b). Rankings of the subpopulations in Network 2 is also reversed for cumulative infection rate: the percentage change is greatest in the non-slum region, while it is greatest for the slum regions in absolute terms.

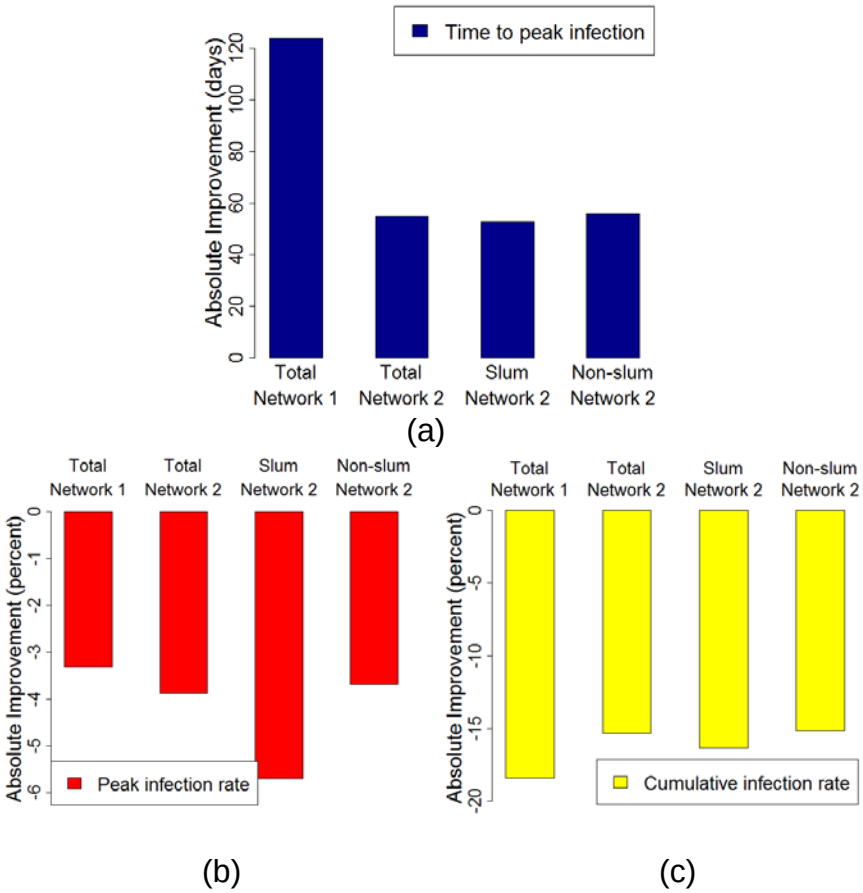


Figure S5: Comparison of absolute difference in improvement; the relative differences are shown in Figure S7. Absolute differences vary across the three parameters, so each is given on a separate scale. Data are summarized in Tables S7 and S9.

Evaluation of Network 2 Home and School Contacts.

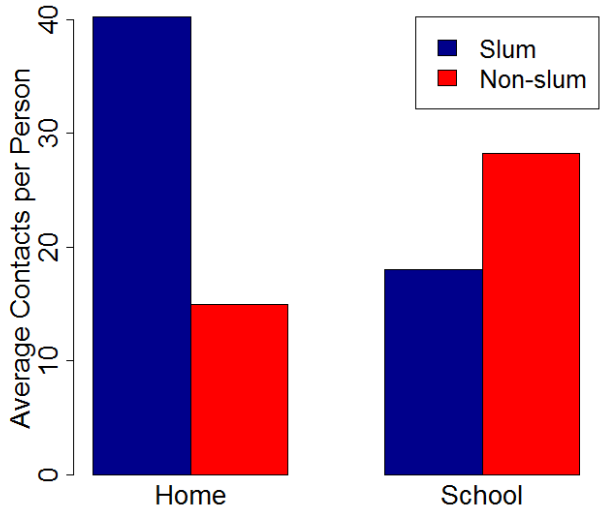


Figure S6: Comparison of average contacts per person in slum and non-slum regions for home and school activity types in Network 2.

Evaluation of Network 2 Edges Transmitting Infection.

Figure S7 provides counts of edges used to transmit infection for a base case simulation in Network 2 of Figure 1 of the main text. Edges are broken down by activity types of people who are interacting during transmission. Data are also broken down by the classifications of individuals interacting (e.g., slum and nonslum, see legend).

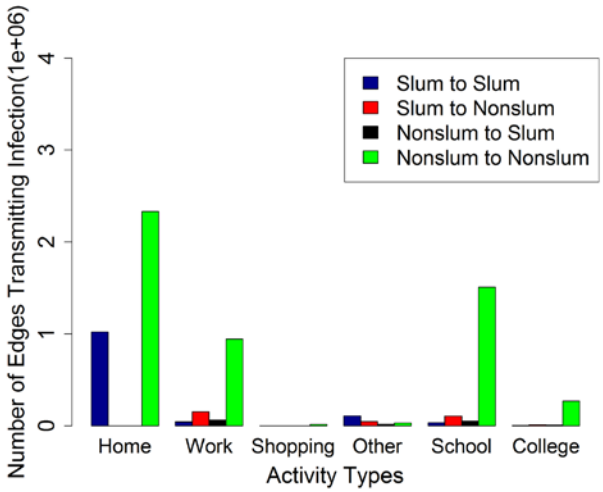


Figure S7. Data for Network 2. Number of edges transmitting infection (in millions) for each of the four types of interactions between slum and nonslum individuals (see legend) and for each activity type. The number of slum-to-nonslum edges is greater than nonslum-to-slum ones because once infection gets into a slum household, it may spread within the household more (because there are more people and connections). Thus, a slum household carries more infection to its interactions with nonslum people. The "Other" activity category, like home activity, shows more edges carrying infection for slum-to-slum interactions than slum-to-nonslum, which is consistent with Figures S4 and S6 of Chen et al.[2], where further network characteristics are given.

References

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