The Impacts of Simultaneous Disease Intervention Decisions on Epidemic Outcomes - Supplementary Information

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1. Asymptomatic Cases

Asymptomatic infections can be prevalent in many diseases, and we thus explore the impact of asymptomatic cases in our model. In these analyses, we use an asymptomatic probability of 50% for infectious cases, and assume an asymptomatic individual is as infectious as a symptomatic one. We also recalibrate parameters to maintain epidemic outcomes similar to the baseline scenario while maintaining the baseline transmission rate of 0.005. In this scenario, we use parameter values of $\lambda = 2.85$, $\gamma = 0.75$, $\theta = 0.403$, and the remaining parameters at baseline values. This will allow us to directly compare the impact of asymptomatic infections.

With low transmission rate, vaccination delay does not impact epidemic size when NPIs are used. (Table 1). When NPIs are not used, epidemic size is minimally affected ($\approx 2.4\%$ difference between no vaccine delay and a 60 day vaccine delay.) With baseline transmission rate, the difference becomes larger (Table 2). With NPIs, final size changes by under 1 percentage point, but without NPIs, the difference is $\approx 8.5\%$. Finally, with a higher transmission rate of $\beta = 0.006$ (Table 3), NPIs cause the final size to change $\approx 2.4\%$ across all vaccine delays, whereas without NPI effects, final size changes by $\approx 12\%$.

Thus, we observe similar effects of NPIs on epidemic final size when there are vaccine delays with asymptomatic cases as we saw without. That is, changes in final size between no delay and longer delays are much smaller when NPIs are incorporated than when they are not.

Considering the effects of differing vaccine efficacy on epidemic outcomes, we see similar results to the case with no asymptomatic infections. With NPIs used in the population, symptomatic epidemic size and vaccine uptake do not show a large change across vaccine efficacies ($\approx 0.3\%$ and 2%, respectively) compared to when NPIs are not included (2.4% difference for final size and 4.5% difference for vaccine uptake, see Tables 4 and 5).

In general, the main qualitative results are similar to when there are asymptomatic infections to when there are not. When NPIs are included, vaccine availability delays and changes in vaccine efficacy do not change epidemic final size and vaccine uptake as significantly compared to scenarios where NPIs are not incorporated.

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Table 1: **Epidemic final sizes (symptomatic cases only) with delayed vaccine availability.** $\beta = 0.004$

Delay	**Final Size (with NPIs) ±95% CI**	**Final Size (without NPIs) ±95% CI**
0	0.03839 ± 0.0025	0.0932 ± 0.0013
10	0.0381 ± 0.0026	0.0924 ± 0.0014
20	0.0395 ± 0.0024	0.0933 ± 0.0012
30	0.0397 ± 0.0024	0.0940 ± 0.0023
40	0.04086 ± 0.0025	0.1010 ± 0.0019
50	0.04105 ± 0.0023	0.1108 ± 0.0024
60	0.03953 ± 0.0025	0.1173 ± 0.0029

Table 2: **Epidemic final sizes (symptomatic cases only) with delayed vaccine availability.** $\beta = 0.005$

Delay	**Final Size (with NPIs) ±95% CI**	**Final Size (without NPIs) ±95% CI**
0	0.0816 ± 0.0016	0.1107 ± 0.0006127
10	0.0826 ± 0.0013	0.1111 ± 0.0006301
20	0.0821 ± 0.0012	0.1145 ± 0.0007419
30	0.0817 ± 0.0013	0.1313 ± 0.0022
40	0.0838 ± 0.0014	0.1648 ± 0.0031
50	0.0847 ± 0.0018	0.1855 ± 0.0031
60	0.0864 ± 0.0015	0.1958 ± 0.0023

Table 3: **Epidemic final sizes (symptomatic cases only) with delayed vaccine availability.** $\beta = 0.006$

Delay	**Final Size (with NPIs) ±95% CI**	**Final Size (without NPIs) ±95% CI**
0	0.0987 ± 0.0006992	0.1236 ± 0.0006546
10	0.0985 ± 0.0006611	0.1225 ± 0.0006434
20	0.0994 ± 0.0006425	0.1373 ± 0.0016
30	0.1059 ± 0.0009648	0.1898 ± 0.0038
40	0.1130 ± 0.0013	0.2288 ± 0.0027
50	0.1202 ± 0.0013	0.2407 ± 0.0017
60	0.1228 ± 0.0014	0.2451 ± 0.0011

Table 4: **Epidemic final sizes corresponding to vaccine efficacy (symptomatic cases only).**

Efficacy	**Final Size (With NPIs) ±95% CI**	**Final Size (Without NPIs) ±95% CI**
0.5	0.0845 ± 0.0012	0.1350 ± 0.0008755
0.6	0.0835 ± 0.0014	0.1291 ± 0.0007565
0.7	0.0819 ± 0.0019	0.1231 ± 0.0007093
0.8	0.0819 ± 0.0013	0.1186 ± 0.0008193
0.9	0.0826 ± 0.0013	0.1145 ± 0.0006082
1.0	0.0814 ± 0.0014	0.1111 ± 0.0022

Table 5: **Population vaccine uptake corresponding to vaccine efficacy.**

Efficacy	**Vaccine Uptake (With NPIs)** $\pm 95\%$ **CI**	**Vaccine Uptake (Without NPIs)** $\pm 95\%$ **CI**
0.5	0.4662 ± 0.018	0.7124 ± 0.0037
0.6	0.4604 ± 0.0201	0.7051 ± 0.0036
0.7	0.4449 ± 0.0223	0.6938 ± 0.0037
0.8	0.4408 ± 0.019	0.6850 ± 0.0053
0.9	0.4503 ± 0.019	0.6784 ± 0.0036
1.0	0.4478 ± 0.02	0.6676 ± 0.013

2. Network Types

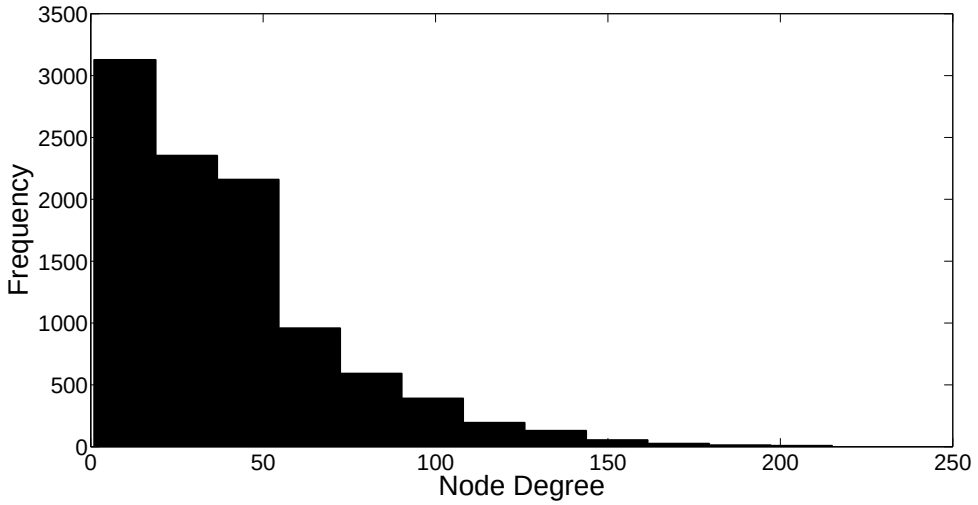


Figure 1: Frequency of node degrees in the empirically based network. The majority of nodes have a degree < 75, whereas fewer nodes have higher degrees. The average node degree is 38.645.

Different network types will have an impact on epidemic outcomes due to contact structures playing a pivotal role in disease transmission. In our model, we initially used an empirically based network. Here, we will look at results stemming from a random network and a power law network. For these two types of networks, we recalibrate the parameters to achieve similar baseline scenarios to the outcomes corresponding to the empirical network.

For the random networks, we use the same average node degree seen in the empirically based network (Figure 1), and we generate new networks each simulation. The parameters used to obtain the same epidemic outcomes as the original baseline scenario are $\lambda = 1.75$, $\gamma = 0.25$, $\theta = 0.28$, $\beta = 0.00585$, and the remaining parameters at baseline values. We note that the transmission rate must be higher with this network structure to achieve the same epidemic final size, and in turn the same vaccine uptake, and NPI use as the empirical network. When either increasing or decreasing the transmission rate, we still use intervals of size 0.001.

With low transmission rate, vaccination delay does not significantly impact epidemic size when NPIs are used. (Table 6). With a transmission rate of $\beta = 0.00585$, the difference becomes larger (Table 7). With NPIs, final size changes by under 1 percentage point, but without NPIs, the difference is $\approx 18\%$, and the difference grows larger the later the vaccine is made available. Finally, with a higher transmission rate of $\beta = 0.00685$ (Table 8), NPIs cause the final size to change $\approx 10\%$ across all vaccine delays, whereas without NPI effects, final size changes by $\approx 41\%$.

Considering the effects of differing vaccine efficacy on epidemic outcomes in the random networks, we see similar results to the case with an empirically based network. With NPIs used in the population, epidemic size and vaccine uptake show changes across vaccine efficacies of $\approx 0.55\%$ and 16%, respectively, compared to when NPIs are not included (3.4% difference for final size and only 1% difference for vaccine uptake, see Tables 9 and 10). An interesting dynamic occurs in the

Table 6: **Epidemic final sizes with delayed vaccine availability (random network).** $\beta = 0.00485$

Delay	**Final Size (with NPIs)** $\pm 95\%$ **CI**	**Final Size (without NPIs)** $\pm 95\%$ **CI**
0	0.0608 ± 0.0047	0.1543 ± 0.0044
10	0.05964 ± 0.0047	0.1527 ± 0.0049
20	0.06297 ± 0.0047	0.1525 ± 0.0054
30	0.0602 ± 0.0049	0.1500 ± 0.0063
40	0.06353 ± 0.0045	0.1545 ± 0.0052
50	0.0602 ± 0.0046	0.1523 ± 0.005
60	0.0602 ± 0.0048	0.1539 ± 0.0049

Table 7: **Epidemic final sizes with delayed vaccine availability (random network).** $\beta = 0.00585$

Delay	**Final Size (with NPIs)** $\pm 95\%$ **CI**	**Final Size (without NPIs)** $\pm 95\%$ **CI**
0	0.1592 ± 0.0015	0.1821 ± 0.0005972
10	0.1591 ± 0.0016	0.1818 ± 0.0005030
20	0.1592 ± 0.0014	0.1816 ± 0.00053807
30	0.1610 ± 0.0013	0.1823 ± 0.0007169
40	0.1602 ± 0.0017	0.2074 ± 0.0062
50	0.1609 ± 0.002	0.2911 ± 0.011
60	0.1649 ± 0.0027	0.3667 ± 0.012

Table 8: **Epidemic final sizes with delayed vaccine availability (random network).** $\beta = 0.00685$

Delay	**Final Size (with NPIs)** $\pm 95\%$ **CI**	**Final Size (without NPIs)** $\pm 95\%$ **CI**
0	0.1779 ± 0.0005021	0.1927 ± 0.0009735
10	0.1781 ± 0.0004927	0.1932 ± 0.001
20	0.1776 ± 0.0004817	0.1933 ± 0.0009566
30	0.1798 ± 0.0012	0.2634 ± 0.0091
40	0.2116 ± 0.0038	0.4638 ± 0.011
50	0.2524 ± 0.0042	0.5780 ± 0.0063
60	0.2739 ± 0.0033	0.6100 ± 0.0042

random network as although final size difference for the range of vaccine efficacy given in tables 9 and 10 with NPIs is much smaller than when there are no NPIs, vaccine uptake increases much more. However, with NPIs, vaccine uptake amongst the population is approximately 20-40% lower than with no NPIs, and produces smaller epidemic sizes.

For the power law networks, we use a Barabási-Albert algorithm with three initial connected nodes to create a contact network for each simulation. The parameters used to obtain the same epidemic outcomes as the original baseline scenario are $\lambda = 1.25$, $\gamma = 0.5$, $\theta = 0.35$, $\beta = 0.075$, and the remaining parameters at baseline values. We note that the transmission rate must be higher with this network structure to achieve the same epidemic final size, and in turn the same vaccine uptake,

Table 9: **Epidemic final sizes corresponding to vaccine efficacy (random network).**

Efficacy	**Final Size (With NPIs) ±95% CI =**	**Final Size (Without NPIs) ±95% CI**
0.5	0.1644 ± 0.001	0.2158 ± 0.0009870
0.6	0.1616 ± 0.0014	0.2059 ± 0.0007589
0.7	0.1617 ± 0.0011	0.1978 ± 0.0006078
0.8	0.1609 ± 0.001	0.1904 ± 0.0005643
0.9	0.1603 ± 0.001	0.1858 ± 0.0004162
1.0	0.1589 ± 0.001	0.1821 ± 0.0004704

Table 10: **Population vaccine uptake corresponding to vaccine efficacy (random network).**

Efficacy	**Vaccine Uptake (With NPIs) ±95% CI**	**Vaccine Uptake (Without NPIs) ±95% CI**
0.5	0.5940 ± 0.039	0.8176 ± 0.0003564
0.6	0.5505 ± 0.041	0.8159 ± 0.0003212
0.7	0.5286 ± 0.042	0.8137 ± 0.0003098
0.8	0.4762 ± 0.042	0.8112 ± 0.0002534
0.9	0.4546 ± 0.042	0.8089 ± 0.0002167
1.0	0.4323 ± 0.043	0.8067 ± 0.0002177

and NPI use as the empirical network. When either increasing or decreasing the transmission rate, we will use intervals of size 0.02.

With a transmission rate of 0.0055, vaccination delay impacts epidemic size by $\approx 4\%$ when NPIs are used and ≈ 11 when they are not (Table 11). With a transmission rate of $\beta = 0.075$, the difference becomes larger (Table 12). With NPIs, final size changes by about 9 percentage points, but without NPIs, the difference is $\approx 23\%$. For both cases, the difference grows larger in the early stages of the epidemic. Finally, with a higher transmission rate of $\beta = 0.0095$ (Table 13), NPIs cause the final size to change $\approx 15\%$ across all vaccine delays, whereas without NPI effects, final size changes by $\approx 31\%$. Again, NPIs reduce epidemic sizes, as well as decrease the change in final size induced by delays in vaccine availability. In the scale free networks we created, the majority of epidemic incidence increase occurs before the 30 day mark of vaccination absence.

Table 11: **Epidemic final sizes with delayed vaccine availability (power law network).** $\beta = 0.055$

Delay	**Final Size (with NPIs) ±95% CI**	**Final Size (without NPIs) ±95% CI**
0	0.1231 ± 0.0014	0.1736 ± 0.000806
10	0.1282 ± 0.0028	0.1805 ± 0.0012
20	0.1411 ± 0.0033	0.2242 ± 0.0038
30	0.1623 ± 0.0017	0.2644 ± 0.0043
40	0.1607 ± 0.0021	0.2822 ± 0.006
50	0.1628 ± 0.0018	0.2869 ± 0.0027
60	0.1638 ± 0.002	0.2875 ± 0.0028

Table 12: **Epidemic final sizes with delayed vaccine availability (power law network).** $\beta = 0.075$

Delay	**Final Size (with NPIs)** $\pm 95\%$ **CI**	**Final Size (without NPIs)** $\pm 95\%$ **CI**
0	0.1685 ± 0.0008614	0.2053 ± 0.0013
10	0.1755 ± 0.0011	0.2253 ± 0.0023
20	0.2318 ± 0.0029	0.3602 ± 0.0057
30	0.2520 ± 0.002	0.4276 ± 0.0028
40	0.2565 ± 0.002	0.4306 ± 0.0024
50	0.2576 ± 0.002	0.4344 ± 0.0029
60	0.2599 ± 0.0021	0.4330 ± 0.0023

Table 13: **Epidemic final sizes with delayed vaccine availability (power law network).** $\beta = 0.095$

Delay	**Final Size (with NPIs)** $\pm 95\%$ **CI**	**Final Size (without NPIs)** $\pm 95\%$ **CI**
0	0.1921 ± 0.0011	0.2316 ± 0.0023
10	0.2124 ± 0.0023	0.2823 ± 0.0057
20	0.3136 ± 0.0031	0.4975 ± 0.0044
30	0.3346 ± 0.0025	0.5418 ± 0.0026
40	0.3427 ± 0.0022	0.5502 ± 0.0026
50	0.3401 ± 0.0021	0.5444 ± 0.0024
60	0.3426 ± 0.002	0.5442 ± 0.0026

Considering the effects of differing vaccine efficacy on epidemic outcomes in the power law networks, we see similar results to the case with an empirically based network. With NPIs used in the population, epidemic size and vaccine uptake show changes across vaccine efficacies of $\approx 3.6\%$ and 2%, respectively, compared to when NPIs are not included (8.8% difference for final size and 4.4% difference for vaccine uptake, see Tables 9 and 10).

Table 14: **Epidemic final sizes corresponding to vaccine efficacy (power law network).**

Efficacy	**Final Size (With NPIs)** $\pm 95\%$ **CI**	**Final Size (Without NPIs)** $\pm 95\%$ **CI**
0.5	0.2040 ± 0.0014	0.2941 ± 0.0017
0.6	0.1982 ± 0.0011	0.2751 ± 0.0016
0.7	0.1922 ± 0.0011	0.2557 ± 0.0014
0.8	0.1816 ± 0.0009980	0.2381 ± 0.0014
0.9	0.1762 ± 0.0008868	0.2219 ± 0.0014
1.0	0.1682 ± 0.0007904	0.2060 ± 0.0013

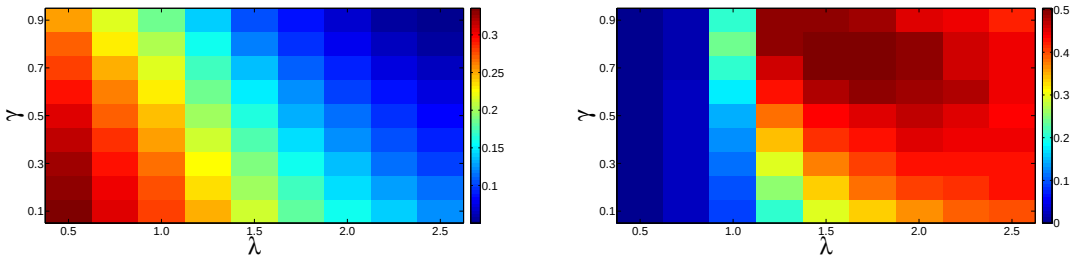
We have seen with these two alternate types of networks that the main results consistently hold. However, each network has unique dynamics that must be taken into account in certain scenarios. Thus, assumptions about network structure and transmission are an important consideration particularly when modelling a specific disease. For example, a transmission network for influenza likely has a different structure than one that would be used to model HIV transmission.

Table 15: **Population vaccine uptake corresponding to vaccine efficacy (power law network).**

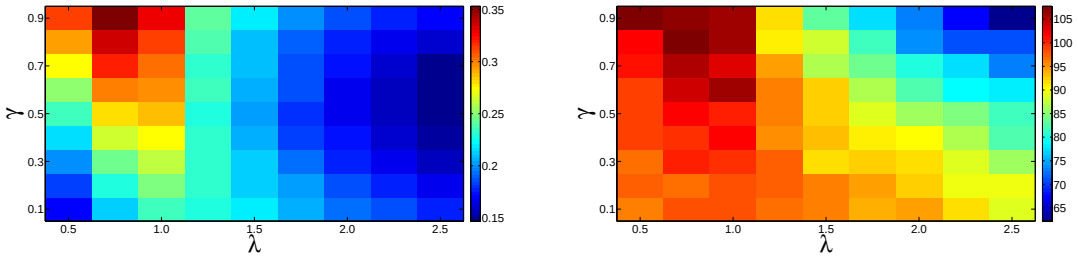
Efficacy	**Vaccine Uptake (With NPIs)** $\pm 95\%$ **CI**	**Vaccine Uptake (Without NPIs)** $\pm 95\%$ **CI**
0.5	0.4504 ± 0.003	0.5416 ± 0.0025
0.6	0.4405 ± 0.0027	0.5321 ± 0.002
0.7	0.4493 ± 0.0029	0.5223 ± 0.0022
0.8	0.4439 ± 0.0028	0.5213 ± 0.0022
0.9	0.4303 ± 0.0025	0.4987 ± 0.0019
1.0	0.4302 ± 0.0026	0.4972 ± 0.0017

3. Pairwise Analysis

We conducted pairwise sensitivity analysis for the behaviour response parameters λ and γ (Figure 2). In total, 81 combinations were used and results of each combination are given as the averages over 500 realizations. We find that increasing λ has the most beneficial effect on decreasing epidemic final size and increasing vaccination rates. Also, increasing γ alongside λ can complement these results decreasing incidence or increasing vaccination further. Increasing both of these parameters can also decrease the NPI use amongst susceptible individuals at the end of an epidemic. This seems counter intuitive, but since more individuals are vaccinating efficaciously and the amount of infected individuals becomes smaller, many in the population do not need to practice strong NPI use. However, increased γ with smaller values of λ can promote NPIs in the population, increasing the use of these self protective measures when an epidemic is more widespread. Finally, an increase in λ and γ will shorten the duration the an epidemic, given that far fewer people are becoming infected.



(a)



(b)

Figure 2: Pairwise sensitivity analysis of parameters λ and γ. (a) cumulative incidence, (b) cumulative vaccination, (c) transmission rate reduction amongst susceptible population, (d) epidemic length. Results averaged over 500 trials.