Online Appendix

The online appendix contains information on all model inputs (Section A), additional information about the use of the online model (Section B), additional information about the standard gamble exercise (Section C), and additional sensitivity analyses (Section D).

Those who wish to use the model as a decision aid for re-opening their university in the fall should visit our website.

A. Complete list of Model Inputs.

Online Table 1 lists all parameters used in the model.

Online Table 1. Total costs and probabilities used as model inputs for estimating the cost-effectiveness of strategies to improve infection control for Covid-19 in a university setting with 16,000 students and 4,500 employees on campus during a 90-day semester.

Parameters	Baseline	Distribution*	Source
Population			
Number of students on campus	16,000	-	Data from Columbia University
Number of staff/faculty on campus	4,500	-	Data from Columbia University
Daily number of close contacts			
Between each student and other students on campus (but not in dorms)	2	Triangular (1, 3, 2)	Expert opinion†
Between each student and staff/faculty on campus	0	Triangular (0, 1, 0)	Expert opinion†
Between each student/staff/faculty and community members outside of campus	3	Triangular (2, 4, 3)	Expert opinion†
Between each staff/faculty and students on campus	1	Triangular (0, 2, 1)	Expert opinion†
Between each staff/faculty and other staff/faculty on campus	1	Triangular (0, 2, 1)	Expert opinion†
Between each staff/faculty and community members outside of campus	2	Triangular (1, 3, 2)	Expert opinion†
Probabilities and rates			
Transmission rate per close contact‡	0.066	Normal (0.066, 0.005)	[1]
Proportion of affiliates immune to COVID-19	0.06	Triangular (0, 0.2, 0.06)	[2]
Progression time for Covid-19			
Incubation time (r_{inc})	5 days	Triangular (3, 14, 5)	[3,4]
Time from infectiousness to symptoms onset (r_s)	2 days	Triangular (1, 3, 2)	[3,4]
Time from exposure to infectiousness	3 days	Probability distribution of r_{inc}	[3,4]

		- probability distribution of r_s	
Duration of infectiousness from symptoms onset	9 days	Triangular (6, 11, 9)	[3,4]
Proportion of symptomatic cases among all exposed people (including the ones initially asymptomatic but became symptomatic eventually)	0.53	Beta (52.53, 59.23596)	[5]
Infection hospitalization rate among students	0.008	Beta (99.192, 12299.81)	[6,7]
Infection hospitalization rate among staff/faculty	0.018	Beta (98.182, 5356.374)	[6,7]
Infection fatality rate among students	0.0002	Beta (99.9798, 499799)	[6]
Infections mortality rate among staff/faculty	0.0015	Beta (99.8485, 66465.82)	[6]
Proportion of students' compliance with stay-home order when they notice their symptoms	0.85	Triangular (0.75, 0.9, 0.85)	Assumption
Proportion of community members' compliance with wearing masks outside of campus	0.78	Triangular (0.72, 0.78, 0.78)	[8,9]
Direct costs (U.S. dollars in 2020 USD)			
Hospitalization	$23,489	-	[10,11]
Funeral cost for infection death	$10,000	Gamma (16, 0.0016)	Assumption
Intervention costs¶			
CDC guidelines			[12]
Adhering to cleaning protocol costs	$318,798	-	[13]
Custodial staff	$979,503	-	[13]
Personal protective equipment	$1,386,898	-	[13]
Enhanced masks	$164,000	-	2 masks/affiliate @$4/mask. Enhanced masks are provided on top of regular masks. The number here only reflects the cost of providing enhanced masks.
Temperature cameras	$485,000	-	10 units @ $12,000/unit and installment cost of $500/unit. In addition, assuming wage for 20 staff operating 8 hrs/day over the entire

			semester at the rate of $25/hr.
PCR test (per test)	$31	-	Internal data for test cost. In addition, assumed personnel time value for 4 personnel at $25/hr for 8 hrs/day for 1500 tests; 30% administrative costs; 10 cents shipping/specimen.
Far UVC lights	$3,630,000	-	$1,000/light + $100 installation, 3,300 lights installed
HVAC Upgrades	$12,000,000	-	Cost for Columbia University¶
Indirect costs (U.S. dollars in 2020 USD)			
Productivity loss for Covid-19 (per person)	$2,800	Gamma (100, 0.03571429)	Assuming 14 days of quarantine at $25/hr for 8 hrs/day
Productivity loss for infection hospitalization (per person)	$4,200	Gamma (100, 0.02380952)	Assuming 21 days of quarantine at $25/hr for 8 hrs/day
Productivity loss for infection death (per student)	$1,950,000	Gamma (100, 5.128205e-05)	Assuming 39 yrs (65-26) work years lost at $50,000/yr. 26 represents the average age of students at Columbia University
Productivity loss for infection death (per staff/faculty)	$950,000	Gamma (100, 0.0001052632)	Assuming 19 yrs (65-46) work years lost at $50,000/yr. 46 represents the average age of staff/faculty at Columbia University
Lost tuition per day† for online vs. in - person classes (per student)	$46	-	Calculated from a student survey average tuition for the Fall of 2020 semester at

			Columbia University
Productivity loss associated with a false-positive test result (per staff/faculty per day)	$450	Gamma (100, 0.2222222)	Assuming losing 18 hrs of leisure time at $25/hr
Intervention effects			
CDC guidelines			
Odds ratio of infection for hand washing/sanitizer	0.45	-	[14]
Odds ratio of regular mask use	0.33	-	[14,15]
Overall effect (odds ratio)	0.1485	Beta (85.0015, 487.3992)	[14,15]
Symptom checking application±			
% improvement in proportion of students' compliance with stay-home order when they notice their symptoms	10%	Triangular (0.75, 0.9, 0.85)+0.1	Assumption
Enhanced masks			
Risk reduction hand sanitizer	0.45	-	[14,15]
Risk reduction N95 (relative to no mask)	0.09	-	[14,15]
Overall effect (odds ratio)	0.04	Beta (95.9095, 2272.226)	
Test for SARS-CoV-2			
Sensitivity	0.95	-	[16]
Specificity	0.95	-	[16]
Temperature camera (fever)			
Sensitivity	25.8	-	[17,18]
Specificity	0.71	-	[18]
Health-related quality of life			
Losses of QALYs for Covid-19 among students	0.09	Beta (90.91, 919.2011)	[19]
Losses of QALYs for Covid-19 among staff/faculty	0.14	Beta (85.86, 527.4257)	Estimated for average age of staff/faculty at Columbia University (46 years old)[19]
Losses of QALYs for hospitalizations	0.6	Beta (39.4, 26.26667)	[19]
Lifetime losses of QALYs for an infection death among students	45.9	(54)*Beta (14.15, 2.497059)	Assuming an average age student (26 years) would have otherwise lived for 80 years at QALYs of 0.85

			estimated from average US population.[19]
Lifetime losses of QALYs for an infection death among staff/faculty	28.9	(34)*Beta (14.15, 2.497059)	Assuming an average age staff/faculty (46 years) would have otherwise lived for 80 years at QALYs of 0.85 estimated from average US population[19]

Note: A close contact is defined as person-to-person contact < 6 feet for > 10 minutes. See Online Appendix for further details on model inputs.
*For triangular distributions, the values listed are baseline value, high, and low. For normal, beta, and gamma distributions, the values listed are the baseline value and error. Some variables had little influence on the model (indicated with a hyphen) and were removed from the Monte Carlo simulation to reduce computing time.
†Expert opinion based on video conferences with the Public Health Committee at Columbia University, which is comprised of a range of infectious disease experts and administrators.
‡The transmission rate assumes that half of close contacts will be at home and half of close contacts will be off campus.
¶Costs reflect actual costs paid by Columbia University including personnel.

B. Additional information regarding the use of the online model

Estimating the prevalence of actively infectious cases in the community

Users who wish to model outcomes for their local university should use predicted rates of prevalent infectious cases /100,000 population in the community surrounding their university from local models at the time of opening and enter these into the online model.[20] Users should be careful to ensure that they enter case numbers that are adjusted for under-reporting and for the duration of infectious illness (5-10 days). Cornell and Harvard University have developed predictive analytics that can spot changes in the R_0 for a given area.[21] Alternatively, it is possible to obtain estimates of the active infectious prevalence from your local health department.

Users should also be careful to change assumptions surrounding the number of contacts between students, students and staff/faculty, between faculty/staff, and between faculty/staff or students with the surrounding community. Ideally, this would be obtained from student survey data. Areas that have a lower level of concern regarding the dangers of COVID-19 may have more close contacts with others and lower rates of mask use. It is therefore important to adjust for both the number of close contacts and the local prevalence of mask use.[8]

CDC guidelines

The CDC provides guidance on procedures that should be put into place prior to re-opening a university.[12] These include mask use, social distancing, improved ventilation, and cleaning measures. All interventions are compared with the CDC guidelines in the online model except for the status quo arm. The CDC does not recommend testing asymptomatic university affiliates for acute infection with SARS-CoV-2 who have not had contact with a known or suspected case of COVID-19, citing a lack of evidence.

However, it does recommend testing of those who are symptomatic or who have had close contacts with known or suspected cases of COVID-19.

Enhanced Mask Use

In July of 2020, roughly 80% of Americans self-reported social distancing and wearing masks most of the time when indoors, and 59% reported wearing masks consistently.[8] These results were obtained by a large but non-representative sample of the United States. Local use can be found on an interactive map and can be entered into the R-shiny interface.

Cotton masks are widely in use, and may reduce transmission by 67% (1-0.33 adjusted odds ratio converted to a risk ratio).[15,22] The quality of masks in use by students may be lower, and the fit may not be a snug. For this reason, universities may wish to supply students with masks. The online model allows the user to define the mask cost and efficacy.

N95 masks are expensive and uncomfortable. However, they are also highly effective, reducing infection by over 90%.[15] The masks supplied by Columbia University are 2-ply and are estimated to be roughly 80% effective at preventing infection with COVID-19 (relative to 67% for masks in prevalent use and 94% for N95 masks).[15]

Not all affiliates appear to use the provided masks, and the university must nevertheless purchase disposable "back up" masks for use by affiliates who forget to bring a mask upon coming to campus. Therefore, we assume that providing these masks will come at their bulk price cost ($4/mask at Columbia University) and that this cost comes over and above what the university would otherwise have spent on masks.

Temperature Screening Cameras

We examined the cost-effectiveness of highly sensitive thermal imaging cameras to be place in the 10 highest foot traffic areas on campus. We assumed 20 guards would operate the cameras, each working 8 hours per day on weekdays. On weekends the cameras would be operated by existing security staff. We used FLIR Systems A700 as a unit as it is standard in the industry (FLIR Systems, Sweden) programmed for temperature screening.

We relied on Priest et al and Quilty et al to determine the sensitivity and specificity of thermal imaging cameras at detecting COVID-19 on entry to buildings. In Priest et al, 3 airlines agreed to first screen passengers using a questionnaire. Symptomatic travelers had throat and nose swabs for influenza B, and had their temperature measured by a tympanic membrane thermometer. They found that thermal imaging cameras are sensitive and specific at detecting fever. However, fever is a poor predictor of test-confirmed influenza B (and likely a poor predictor of COVID-19 infection by extrapolation). The positive predictive value of thermal imagine for influenza B is 3% at a 2% community prevalence of infectious agents.

Quilty et al model the effectiveness of temperature screening cameras at detecting COVID-19 in the context of airport screening. Their model has a R-shiny interface that allows the user to model the sensitivity for screening for COVID-19 after accounting for the participant's responses to symptom screening application questions and the travel time to work. We set this model to a 1-hour commute time with no subjective symptoms of COVID-19 on leaving home.

Because these cameras screen every affiliate on campus for fever every day, they tend to remove affiliates from the campus irrespective of whether they are infected with COVID-19. The results in *de facto* social distancing, and therefore proves to be an effective mechanism for reducing the spread of COVID-19 even if no cases are present. It also reduces on-campus exposure to influenza-like illnesses, thus carrying additional benefits.

Heating, Ventilation, and Air Conditioning (HVAC) Systems and far UVC light
Breathing, talking, and singing are thought to generate small droplets of saliva that can remain suspended in the air for prolonged periods.[23] Both HVAC systems that meet MERV 13 standards and far UVC lighting systems will clear the air of roughly 90% of aerosolized virus within 8 minutes.[24,25] This, in theory, should be adequate to prevent aerosol-based transmission as repeated exposures to small quantities of virus over at least 10 minutes is required to produce an infection.[26]

Unfortunately, the extent to which aerosol transmission accounts for infections is not known. Therefore, we chose to test this option using a 1-way sensitivity analysis examining the proportion of all cases on campus that are aerosol in nature.

Columbia University has a total of 138 air handlers on campus and 135 are now switched to 100% outside air. The filtration has been upgraded from existing systems (MERV 5 to 8) to MERV 13. The cost of this upgrade was obtained from the university.

While far-UVC light may be more effective than air handlers and also kills SARS-CoV-2 on fomites, there are some questions surrounding the safety of far-UVC light; it has not been extensively tested in humans.[24,27] In our one-way sensitivity analyses, we consider these two interventions to be of equal efficacy and to only work on aerosolized particles for simplicity. To the extent that far-UVC light is safe, it will likely be both of lower cost and higher efficacy than installing a new HVAC system.

Infection Hospitalization Rate and Infection Fatality Rate

The infection fatality rate (IFR) and infection hospitalization rate (IHR) can vary greatly by locality.[6,28] We obtained age-specific IFRs from the literature for the US as a whole,[6] and then computed a weighted average rate using the age distribution of students and faculty separately at Columbia University.

For IHRs, we used CDC data to apportion hospitalization risk by age.[7] We then used the age distribution of affiliates at Columbia University to compute a weighted average IHR using a mean US rate from the literature.[6]

While other universities will have different age and risk distributions, we find that including or excluding those over the age of 70 at Columbia University had little impact on our weighted mean values.

C. Student preferences regarding re-opening universities in the Fall of 2020

Graduate students who had both attended in-person classes during the semester and online classes during the lockdown in the Spring of 2020 were identified by departmental administrators in Health Policy and Management in a convenience sample. A total of 46 students participated. Details of the exercises can be found here.

The raw data are presented **in Appendix Table 2**.

Appendix Table 2

Average Risk of Infection accepted	Students willing to attend social gatherings given	Average Annual Tuition willing to	Average Number of times per week going off-campus

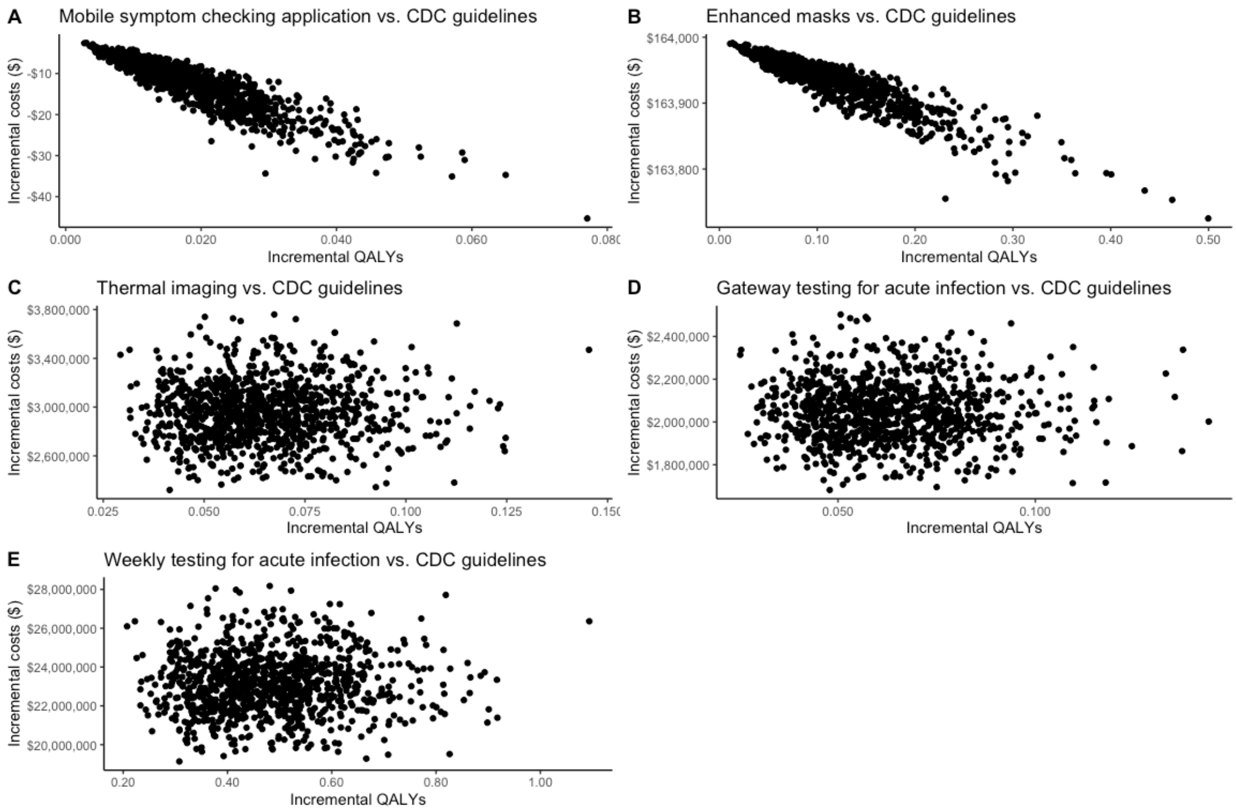
until preference of Online Class	Low/Moderate prevalence of COVID-19 in NYC	pay for Online Classes	
23%	**28%**	**$9,818**	**3.6**

Average Risk of Infection accepted until preference of Online Class	**Willingness to attend social gatherings**	**Number of times per week going off campus**	**Average Annual Tuition willing to pay for Online Classes**
0.125	No	0.5	9050
0.125	Low	5	10000
0.03	No	4	7000
0.003	No	2	10000
0.475	Low	6	10000
0.175	Medium	10	10000
0.0075	No	1	16000
0.275	No	2	5000
0.03	No	1	15000
0	No	10	17000
0.175	No	5	10000
0.175	High	3	10000
0.075	High	8	7500
0.225	No	2	15000
0.03	Medium	3	17000
0.003	No	1	5000
0.075	No	2	12000
0.375	No	2	8000
0.775	Medium	5	10000
0.175	Medium	10	10000
0.575	No	4	NA
1	No	1	0
0.125	No	3	10000
0.075	No	0	15000
0.375	Low	1	10000
0.003	No	0	5000
0.125	Low	3	5000
0.175	Medium	2	10000
0.03	Low	2	10000
0.725	No	0	5000
1	High	4	10000
0.125	Medium	3	10000
0.0075	No	1	8000
0.175	Low	4	10000
0.003	No	0	10000
0.875	High	3	10000
0.03	No	1	10000
0.225	No	3	10000
0.0075	High	2	10200

0.03	No	2	15050
0.275	High	2	15000
0.225	High	7	15000
0.003	No	5	5000
1	No	21	10000
0.03	No	NA	5000
0.075	No	4	5000

D. Additional model outcomes.

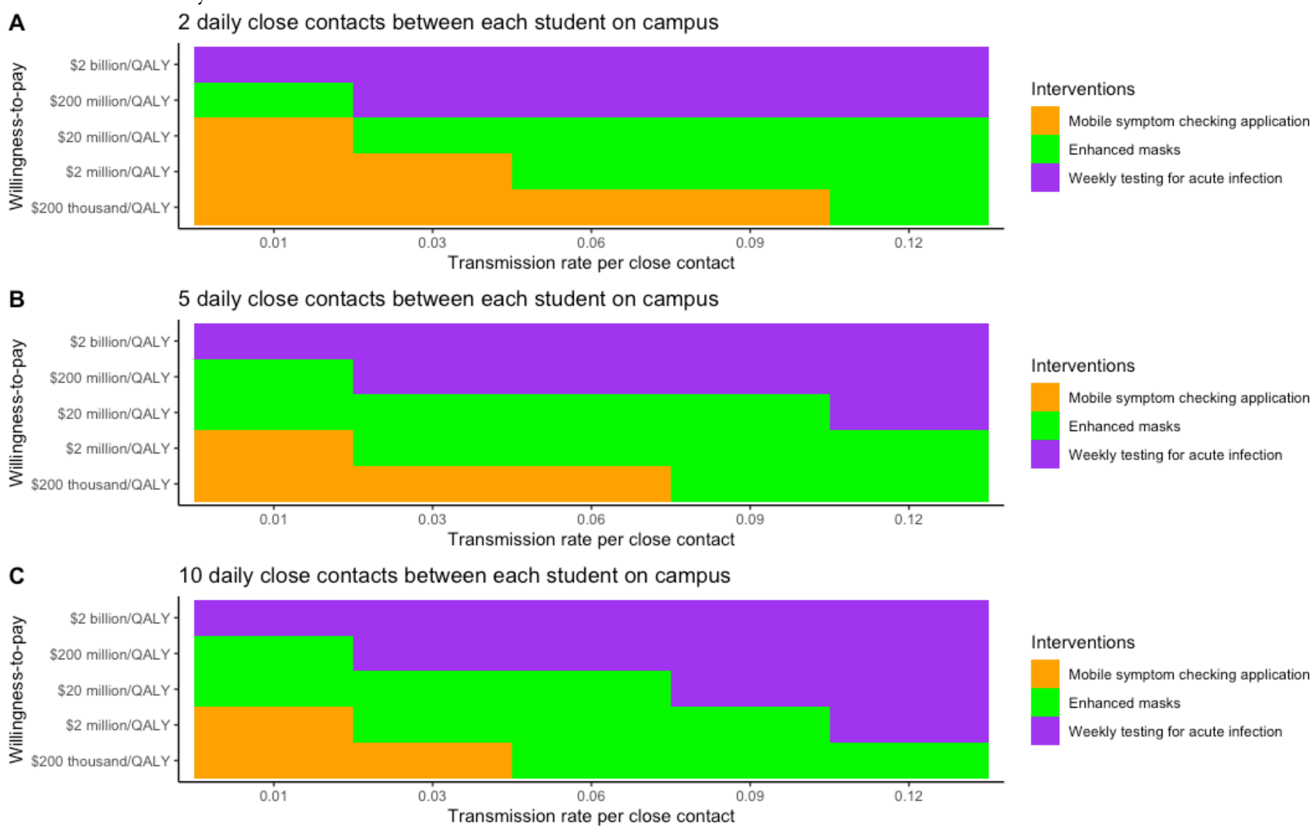
Appendix Figure 1. The cost-effectiveness plane representing difference in costs vs. difference in QALYs for multiple interventions of our model compared to the CDC guidelines (depicted at prevalence rate of 131 infectious cases among 100,000 people).



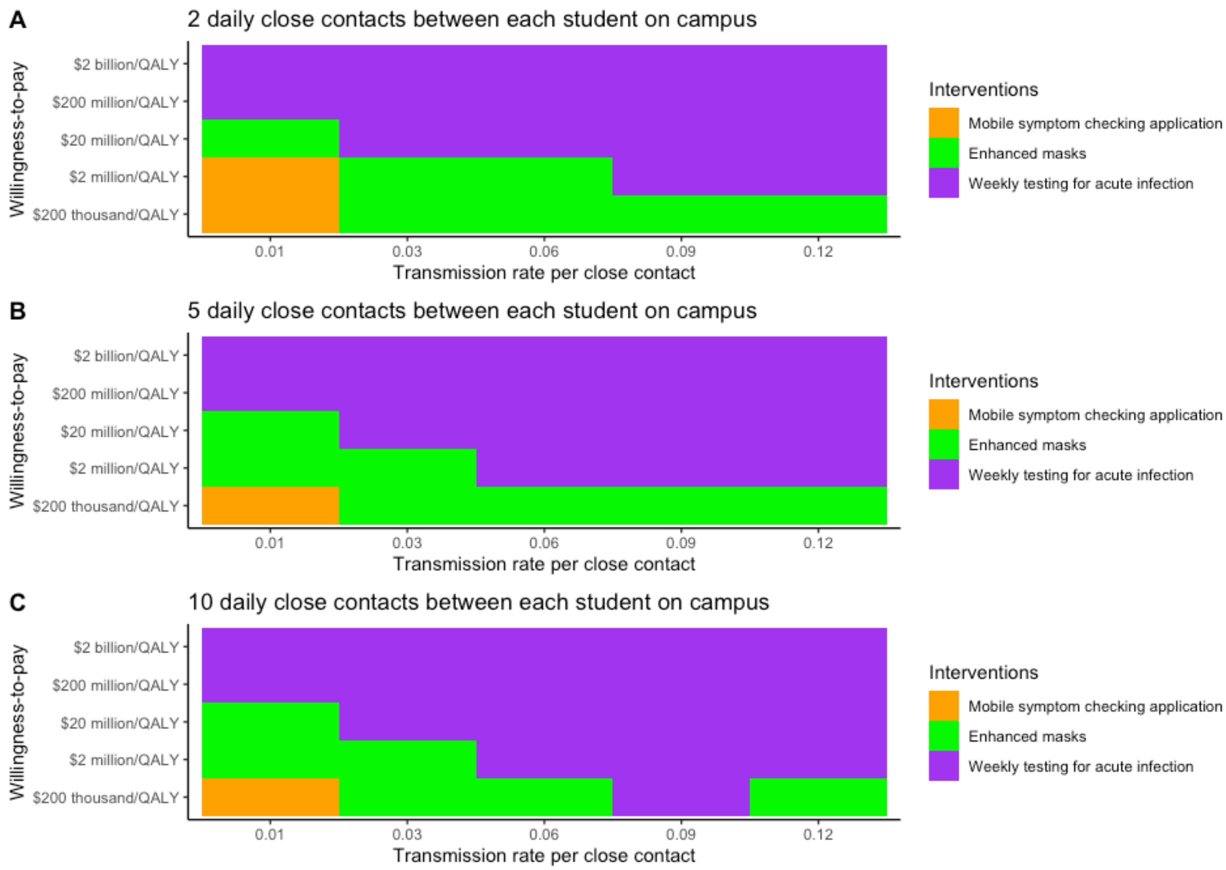
We conducted a number of multi-way sensitivity analyses. **Appendix Figure 2** and **Appendix Figure 3** show the important relationship between the prevalence of actively infectious cases in the community, number of contacts between students off campus (including housing), and the transmission rate. At a prevalence rate of 0.1%, varying the number of contacts and the transmission rate does not have much influence on the ranking of the preferred prevention strategies. However, at a prevalence rate of 1%, we see a gradual shift toward the weekly testing option as the number of close contacts between students rises and the transmission rate rises.

This is important because both the number of contacts and the transmission rate will likely be higher for colleges and universities in which a large proportion of the student body commutes from their family home to school.

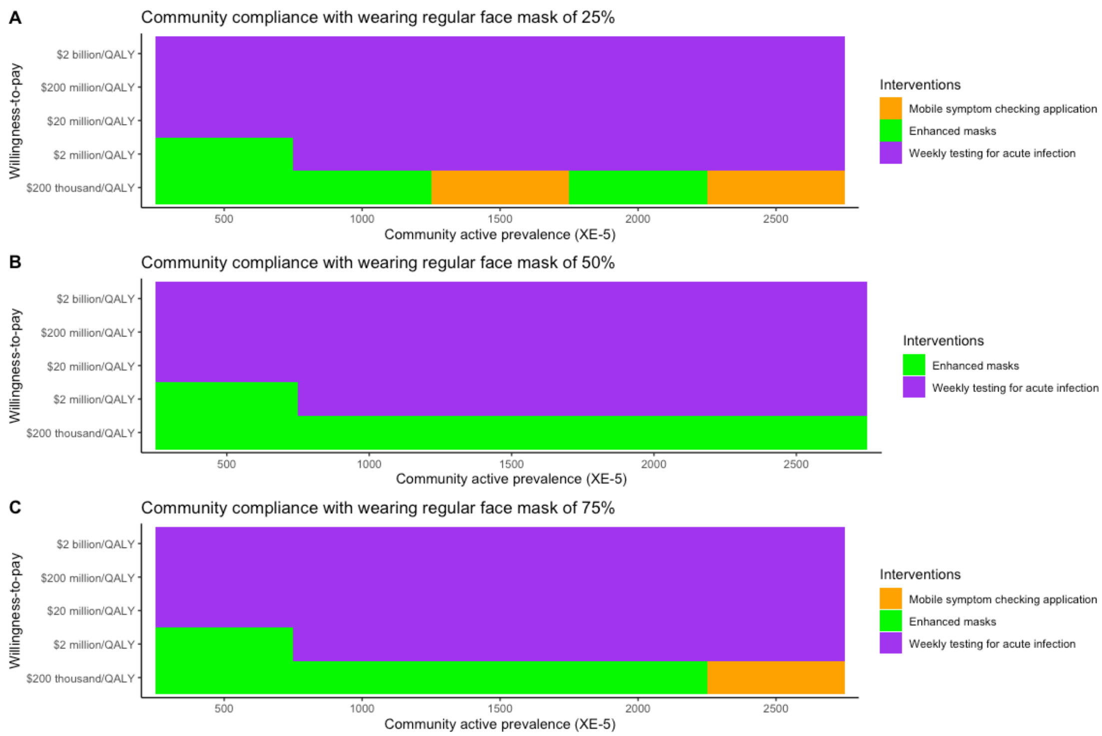
Appendix Figure 2. Three-way sensitivity analysis examining the relationship between the number of close contacts between students on campus, the transmission rate per close student contact, and willingness-to-pay for the top 3 intervention strategies at a 0.1% prevalence rate of actively infectious cases in the community.



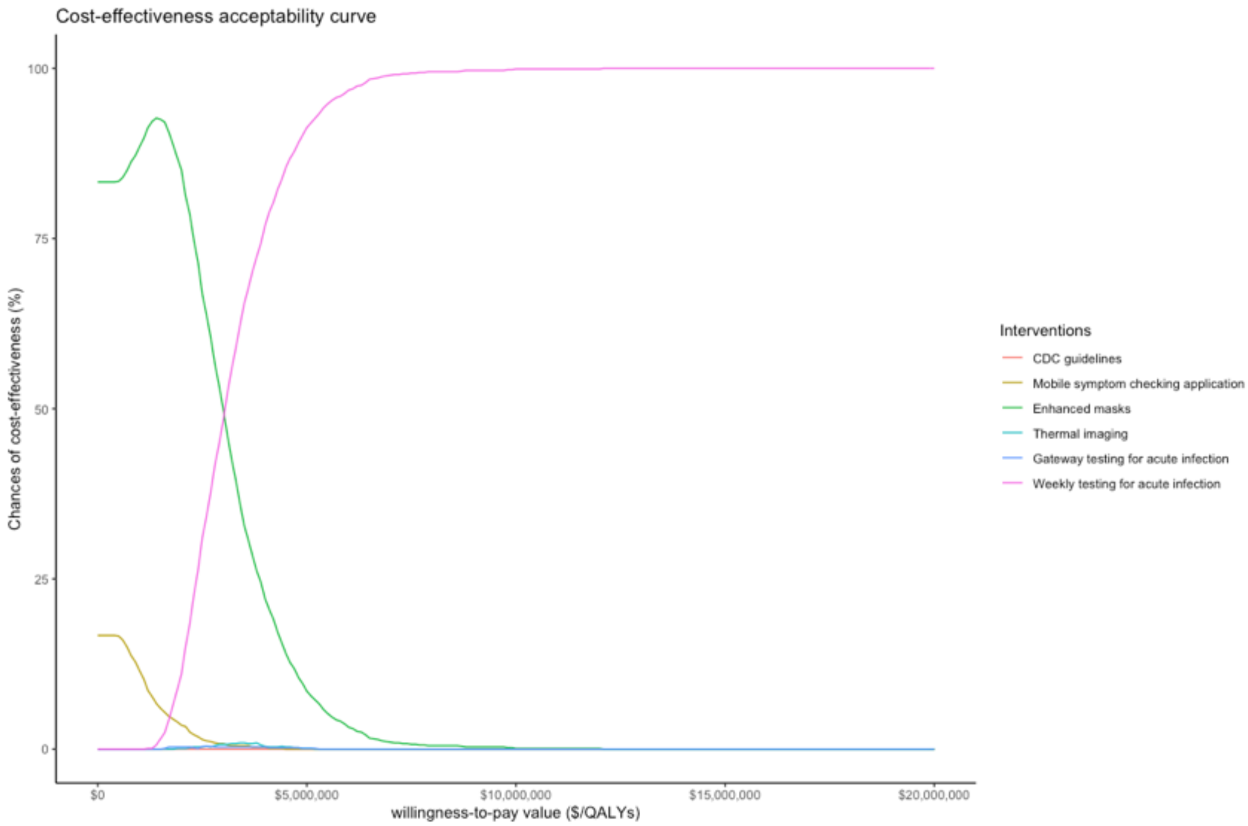
Appendix Figure 3. Three-way sensitivity analysis examining the relationship between the number of close contacts between students on campus, the transmission rate per close student contact, and willingness-to-pay for the top 3 intervention strategies at a 0.1% prevalence rate of actively infectious cases in the community.



Appendix Figure 4 shows that despite conservative assumptions surrounding the cost and use of university-provided 2-ply masks, the strategy competes for dominance with the symptom-checking application intervention.



Appendix Figure 5. Cost-effectiveness acceptability curves. The probability of cost-effectiveness (with maximum net monetary benefit) for multiple interventions at different willingness-to-ay values (calculated at base-case prevalence of 131 cases/100,000 population).



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