informs
https://pubsonline.informs.org/journal/ijaa

INFORMS JOURNAL ON APPLIED ANALYTICS
Articles in Advance, pp. 1–16
ISSN 2644-0865 (print), ISSN 2644-0873 (online)

Modeling the Risk of In-Person Instruction During the Coronavirus Disease 2019 Pandemic

Brian Liu,[a] Yujia Zhang,[b,*] Shane G. Henderson,[c] David B. Shmoys,[c] Peter I. Frazier[c]

[a] Operations Research Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139; [b] Center for Applied Mathematics, Cornell University, Ithaca, New York 14853; [c] School of Operations Research and Information Engineering, Cornell University, Ithaca, New York 14853

*Corresponding author

Contact: briliu@mit.edu, https://orcid.org/0000-0003-2520-1688 (BL); yz685@cornell.edu, https://orcid.org/0000-0001-7991-6385 (YZ); sgh9@cornell.edu, https://orcid.org/0000-0003-1004-4034 (SGH); dbs10@cornell.edu, https://orcid.org/0000-0003-3882-901X (DBS); pf98@cornell.edu, https://orcid.org/0000-0002-3501-3341 (PIF)

Received: October 6, 2023
Revised: February 19, 2024
Accepted: April 4, 2024
Published Online in Articles in Advance: July 12, 2024

https://doi.org/10.1287/inte.2023.0076

Abstract. During the coronavirus disease 2019 (COVID-19) pandemic, safely implementing in-person indoor instruction was a high priority for universities nationwide. To support this effort at Cornell University, we developed a mathematical model for estimating the risk of severe acute respiratory syndrome coronavirus 2 transmission in university classrooms. This model was used to evaluate combinations of feasible interventions for classrooms at Cornell during the COVID-19 pandemic and identify the best set of interventions that allow for higher occupancy levels, matching the prepandemic numbers of in-person courses, despite a limited number of large classrooms. Importantly, we determined that requiring masking in dense classrooms with unrestricted seating when more than 90% of students were vaccinated was easy to implement, incurred little logistical or financial cost, and allowed classes to be held at full capacity. A retrospective analysis at the end of the semester confirmed the model's assessment that the proposed classroom configuration was safe. Our framework is generalizable and was used to support reopening decisions at Stanford University. In addition, our framework is flexible and applies to a wide range of indoor settings. It was repurposed for large university events and gatherings, and it can be used to support planning indoor space use to avoid transmission of infectious diseases across various industries, from secondary schools to movie theaters and restaurants.

History: This paper was refereed.
Funding: This work was supported by the NSF Division of Mathematical Sciences [Grant 2230023].
Supplemental Material: The online appendix is available at https://doi.org/10.1287/inte.2023.0076.

Keywords: decision analysis • education systems operations • epidemiology • stochastic model applications • simulation applications

Introduction

During the initial period of the coronavirus disease 2019 (COVID-19) pandemic, from March 2020 to May 2021, many universities switched entirely to virtual instruction because of a fear that a large outbreak in the student population could quickly overwhelm local healthcare capacity and endanger students, employees, and residents who live near campus (Walke et al. 2020, Cipriano et al. 2021). These interventions were not without costs as they harmed the social well-being and educational outcomes of college students (Dorn et al. 2020, Lee et al. 2021) and damaged the local economies of college towns (Payne 2020, Sullivan 2020). Moreover, prolonged campus shutdowns negatively impact student learning (Dorn et al. 2020) and the livelihoods of those who work around campus (Sullivan 2020). Therefore, safely reopening college campuses to accommodate in-person instruction while avoiding the transmission of infectious diseases is important for universities nationwide.

Cornell University in Ithaca, New York was a leader in safely reopening for residential instruction (Frazier et al. 2022). In the fall of 2020, more than 75% of all students enrolled at the Ithaca campus returned for in-person instruction (Rosenberg 2020b), and extensive testing, contact tracing, and classroom dedensification protocols resulted in fewer than 200 COVID-19 cases throughout the semester out of a population of more than 18,000 students (Cornell COVID-19 Modeling Team 2021b). During this semester, however, although half of the undergraduate students had at least one class with an in-person option (Rosenberg 2020b), only one third of all courses were held in person (Srivastava and Rosenberg 2020). A mandated distancing requirement of six feet, set by the New York State Department of Health (New York State Department of Health 2021b), constrained the number of students that each classroom accommodates. For example, a class with 200 students required a classroom that seated 1,600 people. This mandate dramatically reduced the number of rooms on campus with the capacity to accommodate a large class of students. Furthermore, rooms with poor air circulation were excluded from usage, and only a limited number of classrooms could be retrofitted with heating, ventilation, and air conditioning (HVAC) to enhance ventilation owing to high operational and energy costs. As a result, it was impossible to schedule many classes in person.

Although the fall 2020 semester proved that Cornell University had the ability to safely reopen campus and although the level of in-person instruction during that semester was substantially above that offered by many other universities at the time (Patel and Lee 2022), the number of in-person classes remained significantly below prepandemic levels. This continued in spring 2021; the number of in-person courses offered remained lower than prepandemic levels, and again, most students who returned to campus enrolled in hybrid schedules and took the majority of their classes virtually (Rosenberg 2020a).

Cornell University started to gauge the possibility of offering the full roster of courses in person when planning the fall 2021 semester because much of the community would have been vaccinated at the onset of the semester. However, it faced considerable uncertainty about the safety of offering a full roster of in-person courses. The level of safety associated with using all classrooms, not just rooms with high-quality ventilation, and filling them at greater density was not well understood. Adding to this challenge, the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) Delta variant emerged in the summer of 2021 with increased infectivity compared with the original strain and resistance to vaccines (Callaway 2021). Figure 1 shows a timeline of how the emergence of the Delta variant coincided with our planning period for the fall 2021 semester.

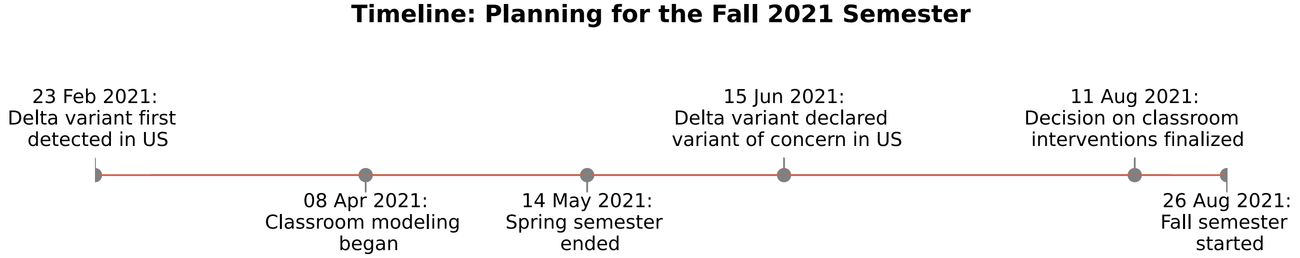
To respond to this uncertainty, our team developed a modeling framework to estimate the risk of COVID-19 transmission in classrooms during the Delta wave of the pandemic. Using this framework, we determined that fully dense classrooms with mandatory masking and without special ventilation or restrictive seating plans resulted in minimal risk to students, graduate student instructors, faculty, and teaching staff throughout the semester. Thus, safe in-person instruction could be offered without further enhancing ventilation in classrooms or developing fixed seating plans for each class, interventions that would have been difficult to implement. Following our recommendations, Cornell University proceeded with dense in-person classes in fall 2021, and empirical evidence aggregated at the end of the semester suggested that classroom transmission was extremely rare (Cornell University COVID-19 Response 2021).

Our modeling framework can be used to support the design of interventions during respiratory disease outbreaks in any context with indoor seating, from kindergarten to 12th grade schools to restaurants and movie theaters. Our framework is flexible and allows a user to estimate the risk of virus transmission in rooms with various configurations. In addition, our framework can evaluate the effectiveness of various interventions, such as vaccines, masking, and ventilation. These functionalities make our framework a valuable tool for modeling indoor transmission.

Contributions to Cornell University

Our modeling framework and analysis guided decision makers at Cornell University in planning for the difficult task of resuming normal teaching operations for the fall 2021 semester. We used our framework to recommend an implementable classroom configuration that allowed classes to meet in full density while ensuring safety for students and instructors. The classroom policies that we recommended—namely, mandatory masking with no distancing or additional ventilation requirements—sufficiently prevented COVID-19 transmission in classrooms. Our retrospective analyses (including contact tracing of COVID-19-positive students and employees, adaptive testing of students in classrooms with positive cases, and genetic sequencing of viral samples) at the end of the semester found that student travel and social events were much more influential drivers of COVID-19 spread on campus compared with classroom transmission (Cornell University 2021b).

Figure 1. (Color online) Timeline of Significant Events During the Planning Period for the Fall 2021 Semester



Note. The Delta variant was declared a variant of concern in the United States halfway through the planning process and influenced our modeling approach and decisions.

We also communicated our modeling approach with transparency and rigor through published analyses and town hall meetings (Cornell COVID-19 Modeling Team 2021a, Cornell University 2021a). Prior to the start of the fall 2021 semester, many in the community expressed concern about the safety of in-person classes. In August 2021, the Cornell Chapter of the American Association of University Professors expressed in a letter to the university president concerns about the risk of teaching in person because of the increased transmissibility of the Delta variant (Lieberwitz 2021). During a faculty and staff town hall the same month, multiple questions were asked about the risk of transmission from teaching class, holding office hours, and masking in classrooms as well as the efficacy of vaccines against the Delta variant (Cornell University 2021a). In addition, multiple faculty members emphasized that the university needed to be more transparent about how classroom safety was assessed (Cornell Faculty 2021).

We developed and communicated our modeling framework to reassure the community that in-person instruction was safe using transparent, data-driven methods. As a result, Cornell University was able to more effectively communicate and inform instructors, teaching assistants, students, and the broader community that returning to normal teaching operations had minimal risk.

Beyond classrooms, we also used our modeling framework to evaluate the risk of holding and attending other university events, such as homecoming, concerts, holiday events, sporting events, and graduation. These analyses informed executive-level decisions on which events to hold throughout the fall 2021 semester. As a result, we found our modeling approach to be useful for evaluating the risk of virus transmission in many indoor settings.

Our modeling framework and analyses were widely distributed and influenced return-to-campus decisions at other universities. Notably, Stanford University cited our analyses in their decision to return to on-campus instruction for fall 2021 (Stanford University 2021). We believe that our success, along with the flexibility and generalizability of our modeling approach, makes our framework a useful tool for managing indoor operations during respiratory disease outbreaks and a valuable contribution toward mitigating the impacts of pandemics.

Related Work

Mathematical modeling was crucial for supporting college reopening decisions during the pandemic. In 2020, universities employed optimization tools in designing course schedules to satisfy multiple decision criteria (Navabi-Shirazi et al. 2022), such as minimizing student interactions (Gore et al. 2022) and maximizing the number of in-person courses offered (Johnson and Wilson 2022). These modeling approaches allowed universities to resume in-person instruction in limited capacities in accordance with social distancing regulations.

Multiple studies have evaluated the risk associated with classroom instruction. These models either use high-fidelity, yet time-consuming, computational fluid dynamics simulation (Foster and Kinzel 2021, Mohamadi and Fazeli 2022) or simulate airborne transmission probabilistically without accounting for the spatial locations of susceptible students (Bazant and Bush 2021, Hekmati et al. 2022, Jimenez and Peng 2024). Our work provides value in that we assessed the risk of in-person instruction when social distancing regulations were relaxed, an important consideration when returning to prepandemic levels of in-person instruction. We model the spatial variation in transmission in a tractable way. Coupled with quantification of parameter uncertainty, our framework provides efficient and robust assessment of different classroom settings in practical situations.

The rest of this paper is organized as follows. First, we describe in detail the challenges faced by Cornell University when planning for the fall 2021 semester. We then explain our framework for estimating the risk of COVID-19 transmission in classrooms, which includes mathematical modeling and a computer simulation. We apply our framework to evaluate different interventions and develop a strategy to safely operate dense in-person classrooms that was recommended to university leadership. We conclude with a retrospective evaluation of our model's validity and discuss its broader impact beyond modeling transmission in classrooms. Further details of our model are presented in the Online Appendix.

Problem Statement

While planning for the fall 2021 semester, Cornell University aimed to offer as many in-person classes as possible while maintaining classroom safety. For the fall 2020 and spring 2021 semesters, it had held only a limited number of dedensified classes, where the students were spaced six feet apart. The constraint of having a finite number of classrooms on campus posed a challenge as expanding in-person classes elevates student density in classrooms, potentially heightening the risk of indoor COVID-19 transmission. To mitigate this potential for elevated transmission risk, Cornell needed to implement classroom interventions. Interventions under consideration included requiring masking, improving ventilation, increasing social distancing, and assigning seats randomly. (Assigning seats randomly reduces the risk that unvaccinated students, who are more vulnerable to infection and have higher transmission when infected, would sit together in socially connected groups.) At the time, we had a limited understanding of the effectiveness of these interventions in preventing disease spread, whether deployed individually or combined. Amid such uncertainty, one major goal of our modeling work was to identify a combination of interventions to efficiently curb disease transmission within classrooms, all while maintaining a reasonable cost.

Cornell University also faced additional concerns in the months leading up to the fall 2021 semester. The more infectious Delta variant of COVID-19 was spreading globally and was responsible for a deadly second wave in India (Tareq et al. 2021). There was concern that the variant would spread to the United States and quickly become the dominant strain. Although many students were fully vaccinated, the vaccine's efficacy against Delta was uncertain. Therefore, the goal of our modeling work was to understand what classroom interventions were needed to safely hold dense in-person classes and to assess and communicate how these interventions addressed the concerns that we faced heading into the fall 2021 semester. We further discuss classroom density, classroom interventions, and the Delta variant below.

Classroom Density

During the fall 2020 semester, only one third of courses were offered with an in-person option (Srivastava and Rosenberg 2020). Although the majority of students returned to Ithaca, few students were in classrooms on any given day during the semester. As such, the university had the ability to aggressively dedensify classrooms to reduce the potential for in-person transmission. All classrooms were configured to be socially distanced, where students were seated six feet apart (Cornell University CTRO 2020). Figure 2 shows the floor plan of a socially distanced classroom, Olin Hall 155, that normally accommodates 287 students during normal university operations. In fall 2020, with social distancing, the maximum capacity of the hall was 26 students, a 90% reduction from the prepandemic capacity.

Overall, social distancing reduced campus-wide classroom capacity by 87%. This reduced capacity was sufficient for the fall 2020 semester, where only a fraction of courses were offered in person under reduced schedules. However, maintaining the same distancing level for the increased in-person course schedule for fall 2021 required each room to be used for more than 24 hours each day.

Thus, further analysis was necessary to assess the safety of increasing classroom density.

Classroom Interventions

Cornell University considered a set of potential interventions to improve classroom safety that included requiring masking, improving ventilation, increasing social distancing, and assigning seats randomly in classrooms. These interventions faced varying implementation difficulties (Table 1). For example, requiring masking was the easiest intervention to execute because the requirement could be enacted impromptu by the administration. Assigning seats randomly required in-advance planning to develop seating plans before the start of the semester. These randomized seating plans reduced the chance that unvaccinated students, who have higher susceptibility and transmissibility when infected, sit together in groups. It was even more difficult to increase social distancing because doing so reduces classroom capacity and limits the number of in-person courses offered. Classes would also need to meet at inconvenient times (late night or early mornings) to accommodate reduced classroom capacity. Finally, increasing ventilation in classrooms was the most difficult intervention to implement owing to the cost of retrofitting all classrooms with HVAC equipment. Such improvements were only made in summer 2020 for the largest classrooms at Cornell (classrooms with more than 100 seats that were used for socially distanced instruction in the fall 2020 and spring 2021 semesters).

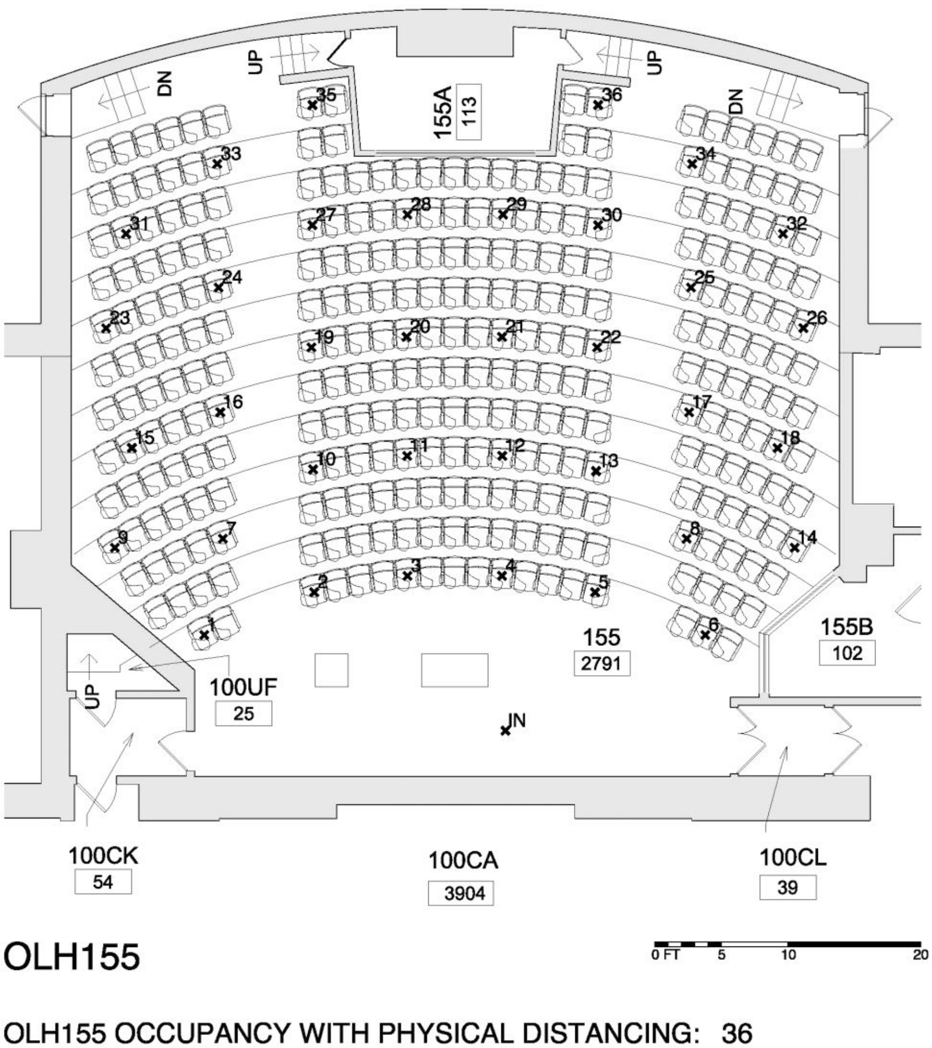
In the Assumptions and Parameters section in the Online Appendix, we describe how we modeled classroom interventions to estimate their efficacy before the start of the semester. This analysis informed Cornell on the interventions needed to ensure safety.

Delta Variant Uncertainties

Figure 3 shows daily COVID-19 case counts in New York State in 2021. The dotted-dashed line indicates the first date when the majority of cases in New York City were determined to be from the Delta variant (New York State Department of Health 2021a). The total daily case count in the state rose steadily from that date until the start of the fall 2021 semester, which is indicated by the red dashed line in Figure 3. In retrospect, it is apparent that the semester started during the peak of the Delta wave of the pandemic.

The emerging Delta wave presented challenges when planning for the fall 2021 semester. First, although the Delta variant drove an increase in cases during the summer of 2021, the exact increase in Delta's infectivity compared with the previous strains was not well understood at the time when Cornell University needed to decide on classroom density. In addition, the literature on vaccine efficacy (VE) against the Delta variant was sparse. Preliminary reports from the United Kingdom and Israel were not encouraging; early studies from the UK National Health Service (Andrews et al. 2021) and the Israel Health Ministry (Israel Ministry of Health 2021) estimated the BNT162b2 Pfizer vaccine efficacy to be 88% and 39%, respectively, against symptomatic illness from the Delta variant. In context, the BNT162b2 Pfizer vaccine achieved vaccine efficacy of 95% against the original strain in clinical trials (Polack et al. 2020).

Figure 2. Floor Plan of Olin 155, a Large Lecture Hall at Cornell University



Notes. The socially distanced seating configuration used in fall 2020 is marked with "x." Only 36 seats were used among the 287 seats available.

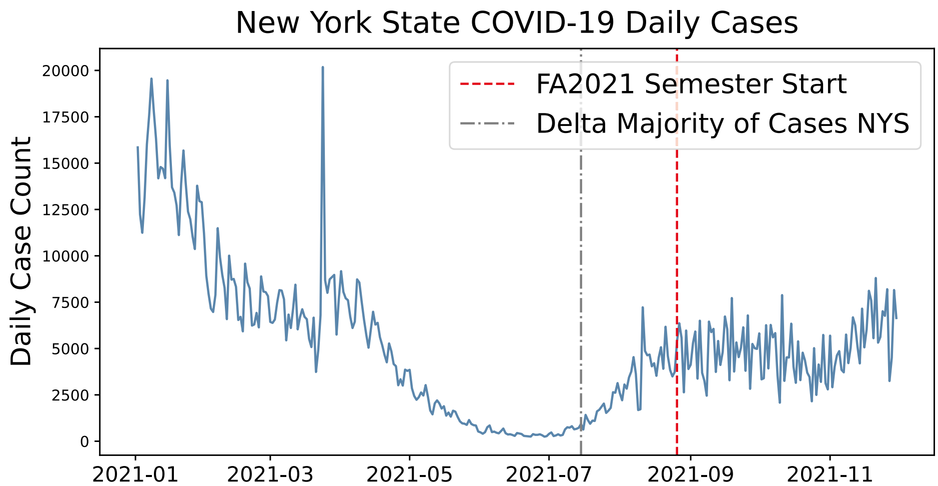
The Assumptions and Parameters section in the Online Appendix explains how we estimated the Delta variant's increased infectivity and decreased vaccine efficacy to produce models of classroom risk robust to uncertainty in both parameters. We used these models to determine whether Cornell University could safely hold in-person classes during the Delta wave of the pandemic.

Table 1. Table of Potential Interventions and Associated Implementation Difficulty

Intervention/difficulty	Easy	Medium	Hard
Require masking	• Instant implementation • No effect on class capacity	—	—
Implement seating policy	—	• Time consuming to implement • No effect on class capacity	—
Increase distancing	—	• Time consuming to implement • Reduces class capacity	—
Increase ventilation	—	—	• Time consuming to implement • Expensive equipment • No effect on class capacity

Note. Medium- and hard-level interventions must be planned out months before the start of the semester.

Figure 3. (Color online) Daily COVID-19 Case Counts for New York State (NYS) Based on Reports from State and Local Health Agencies (New York Times 2021)



Notes. The dotted-dashed line shows when the majority of cases in New York City were first determined to be from the Delta variant. The university started its fall 2021 semester roughly two months later at the peak of the Delta wave.

Modeling Framework

The modeling framework we developed consists of two parts: a mathematical model used to estimate transmission risk between individuals under different conditions and a simulation tool used to evaluate overall classroom risk. We sketch the main ideas here and provide a full description of our methodologies in the Online Appendix.

Main Assumptions and Parameters

Our models rely on a set of parameters, the values of which are key to the predictions, and we estimated parameter values from the literature available at the time of our analysis. For parameters with high uncertainty, we imposed reasonably chosen prior distributions on their values rather than using point estimates. Our assumptions were influenced by our previous work on developing epidemiological models for COVID-19 at Cornell University (Frazier et al. 2022).

We assumed that the Delta variant would be dominant at Cornell at the start of the fall 2021 semester and would be 2.4 times as transmissible as the original COVID-19 strain (Callaway 2021, Washington et al. 2021). We conservatively estimated 90% of the undergraduate population to be fully vaccinated at the start of the semester. Among the vaccinated population, we estimated the distributions of VE against infection and VE against transmission to be centered around 52% and 51%, respectively. These estimates were obtained by weighting the results from several different studies by their sample size. We estimated that masking either the source or susceptible individual reduced transmission probability by 50%–80%. Finally, we assumed perfect compliance with any masking guidelines given by Cornell because in previous semesters, compliance to COVID-19 regulations was very high.

Mathematical Model of Transmission

Given an infectious person in a classroom, we decomposed the risk of transmission into a short-range component and a long-range component, each representing a major mode of SARS-CoV-2 transmission (Centers for Disease Control and Prevention 2021b). The short-range component models transmission because of the deposition of virus-containing respiratory droplets onto exposed mucous membranes; the long-range component models transmission because of the inhalation of virus-containing aerosols or fine droplets. In both components, we used an exponential dose-response model (Watanabe et al. 2010), where the dose is the amount of virus that a susceptible individual is exposed to. According to the dose-response model, the probability that a susceptible individual becomes infected approaches one exponentially with the increase in dose.

Short-Range Transmission. In short-range transmission, the source exhales virus-containing droplets, which are large, heavy particles that tend to deposit on the ground or other surfaces. As the droplets are heavy and cannot travel far, the concentration of droplets in the air decreases with the distance from the source case (Mittal et al. 2020).

To model the fact that students mostly face the instructor, who typically stands in the front of the classroom, we assumed that the source case emits virus particles in a cone of directions toward the front; we call this set of directions the source case's *cone of exposure*.

We modeled the transmission probability in two dimensions, accounting for the distance and the angle of the susceptible individual relative to the source case.

We used maximum likelihood estimation to fit the model parameters (including the angle of the cone of exposure) based on a large data set on COVID-19 transmission aboard high-speed trains in China (Hu et al. 2021), assuming that all secondary infections in the data were because of short-range transmission. The data set gave us the relative positions between infectious index cases on the train and nearby susceptible passengers as well as the subsequent case incidence rates among the susceptible passengers. The seating configuration of the train car is similar to a lecture hall, where all individuals face the same direction and are spaced apart by rows of seats. To the best of our knowledge, this data set was the best available at the time we fit our model.

Long-Range Transmission. We used the model and parameters in Schijven et al. (2021) and modeled long-range transmission by quantifying the concentration of virus-containing aerosols or fine droplets suspended in the air (hereafter, we call them "aerosols"). The model assumed that aerosols are distributed uniformly across the room. As a result, the probability of transmission does not depend on distance or angle from the source and only depends on the rate of aerosol emission from the infectious source, the duration of exposure, room volume, and the level of ventilation.

Overall Risk. We combined the estimated short-range and long-range transmission risks by taking the larger of the two.

When estimating the parameters for the short-range model, we assumed that all secondary infections in Hu et al. (2021) were because of short-range transmission, whereas in reality, some cases may have arisen from long-range transmission. Therefore, the estimates for the short-range model may implicitly include some effect of long-range transmission. Setting the overall risk to the maximum, rather than the sum, of the two risks prevents overestimation. In fact, the simulated short-range risk was usually one to two orders of magnitude larger than the long-range risk within three meters, so it dominated the overall risk for those exposed to it. This is consistent with Public Health Ontario (2022), which found that shorter distance usually implies higher transmission risk.

We assumed that instructors are sufficiently distanced from the students such that short-range transmission is not possible. In our model, the risk from short-range transmission is negligible after six feet of distancing, and we assumed, based on prior semesters, that most instructors spend the majority of their time more than six feet away from students.

We did not explicitly model an infectious instructor because case investigations in the 2020–2021 academic year did not reveal any faculty or student infections that were linked to classroom-based transmission (Cornell University 2021a), and faculty prevalence was much lower than that of students. In addition, the number of students in a class was typically much larger than the number of instructors. Moreover, even if the instructor was infectious in addition to an infectious student in the classroom, this merely approximately doubles the risk because of long-range transmission for each susceptible student. For the susceptible students most at risk (i.e., those sitting in the proximity of the infectious student), the risk from short-range transmission dominates that from long-range transmission by two orders of magnitude. Therefore, the expected number of secondary transmissions remains almost the same regardless of the instructor's infection status.

Reflections. We developed this modeling framework in summer 2021 to support reopening decisions at Cornell University for the fall 2021 semester. As the body of COVID-19-related literature expands, we recommend these modifications to our framework for future use.

1. Evaluate and compare other theoretical models for estimating the risk of COVID-19 transmission through droplets and aerosols (Bazant and Bush 2021, Mirzaei et al. 2021). In addition, calibrate the model to more data sets that shed light on COVID-19 transmission in enclosed spaces, such as in restaurants (Cheng et al. 2022) and theaters (Adzic et al. 2022), as well as adjust for more recent variants, such as Omicron (Ji et al. 2022).

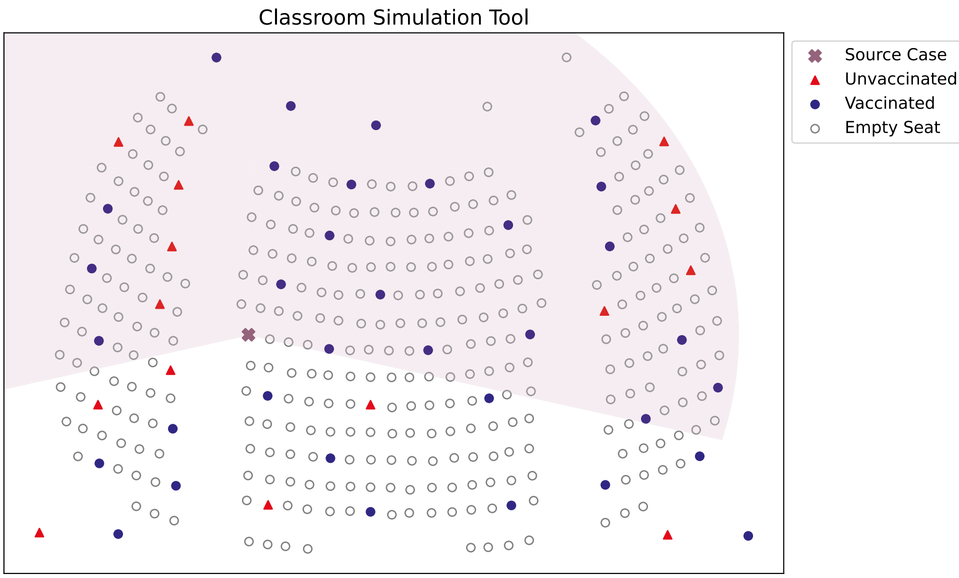
2. Update the estimates of virus transmissibility and vaccine efficacy based on the most up-to-date findings (Ciotti et al. 2022, Wan et al. 2023).

Classroom Simulation Tool

In conjunction with our mathematical classroom model, our simulation tool allowed us to estimate the risk of classroom transmission along with the effectiveness of various interventions, such as masking, social distancing, and increased ventilation. Figure 4 presents an illustration of the classroom simulation tool for a large lecture hall.

For each parameter setting (density level, vaccination rate, and vaccine efficacy), we estimated the expected number of secondary infections in the classroom over a one-hour period given one infectious source case among 50 students averaged over 500 trials. (We omitted the scenarios where there were two or more source cases in the same classroom at the same time. Such scenarios were unlikely compared with scenarios with one source case because prevalence was low, so they contributed little to overall risk. Further discussion is given

Figure 4. (Color online) Example Illustration of the Classroom Simulation Tool



Notes. The **X** indicates the infectious source case, and the cone indicates the cone of exposure, the set of directions in which the source case is modeled as emitting virus particles. Unvaccinated and vaccinated students are represented with triangles and dots, respectively. The instructor is located on a stage sufficiently distanced from the class, far above the top margin of the illustration.

in the Simulation section in the Online Appendix.) For each trial, we randomly generated a seating configuration and vaccination statuses among the students, and we randomly drew a student to be the source case. We repeated this for all combinations of density level, vaccination rate, and vaccine efficacy. We assumed that everyone was unmasked in the simulation. The effect of masking, modeled as an uncertain parameter with a normal prior, can be directly imposed on the results above through multiplication.

Interventions and Scenarios Evaluated

Combining the mathematical model and classroom simulation tool, we evaluated several interventions (masking, seating policy, distancing, and ventilation) across different scenarios. Table 2 summarizes the possible interventions along with their effectiveness against short-range and long-range transmission. We discuss these interventions and scenarios in further detail below.

Table 2. Effectiveness of Intervention Methods at Reducing Short- and Long-Range Transmissions

Intervention/reduction in transmission	Short range	Long range
Masking	✓	✓
Seating policy	✓	—
Distancing	✓	—
Ventilation	—	✓

Masking. Based on experimental and observational studies, we assumed the masking effectiveness against transmission to range from 50% to 80% if either the infectious individual or the susceptible individual was masked (see the details in the Assumptions and Parameters section in the Online Appendix). If both of them were masked, the risk of transmission is reduced by 75%–96%.

We evaluated the intervention of masking for the entirety of the fall 2021 semester, and we assumed that there was perfect compliance with the masking mandate, consistent with the high compliance observed in previous semesters (Cornell University 2021a).

Seating Policy. We considered two different seating policies: (1) randomly assign students to seats and enforce that students always sit in their assigned seats (*fixed seating*) and (2) allow students to sit wherever they want (*unrestricted seating*).

Unrestricted seating had the potential to be more risky in that unvaccinated students could potentially group together. This results in a higher expected number of transmissions because unvaccinated students were more susceptible to COVID-19 infection and had a higher transmissibility if infected (de Gier et al. 2021, Lopez Bernal et al. 2021).

On the other hand, fixed seating was operationally difficult to implement. Our initial simulations showed that the fixed and unrestricted seating policies lead to comparable risk (see Figure A.2 in the Online Appendix). As a result, Cornell University adopted the unrestricted seating policy; all simulation results shown here are thus based on unrestricted seating.

Social Distancing. We evaluated three social distancing options. In *fully dense* seating, the default spacing for lecture halls before the pandemic, students were distanced one foot apart from each other in the classroom. In *moderately dense* seating, students were distanced three feet apart. In *distanced* seating, students were seated six feet apart. This last configuration was used in the 2020–2021 academic year during the pandemic.

Ventilation. For an infectious source case, we assumed that aerosol viral particles were emitted continuously over the hour at a constant rate and were immediately distributed evenly across the room once emitted. We quantified ventilation rate by measuring how often air was exchanged from the room in the unit of air exchanges per hour (ACH), and we assumed that air exchanges happen evenly over time. According to Cornell University's Facilities Department, most classrooms had a ventilation rate of one ACH. We assumed that this rate reduced the amount of viral aerosols accumulated in the classroom over an hour by half relative to having no ventilation (American Society of Heating, Refrigerating and Air Conditioning Engineers 2002).

We evaluated the worst case, where a poorly ventilated room had zero ACH and the risk of aerosol transmission was not reduced at all by ventilation. In addition, we evaluated the intervention where ventilation was improved to three ACH, which reduced the overall dose of transmission from aerosols by a factor of four relative to no ventilation.

Class Type. The type of class determines the intensity of respiratory activity that occurs in the room, which corresponds to different rates of viral aerosol emission. We assumed that breathing (without other respiratory activities) was the dominant type of respiratory activity for students attending lectures and that the effect of occasional speaking (e.g., asking and answering questions) was negligible. However, our simulation is also able to handle activities, such as talking and singing.

Risk over the Semester

Given a set of interventions, we adopted the following procedure to assess the risk of transmission for students and instructors across the entire semester. More details are given in the Assumptions and Parameters section in the Online Appendix. We only considered undergraduate students, but our results easily translate to graduate or professional students, who typically take fewer classes.

We first used our classroom simulation tool to estimate the risk of transmission per hour spent in the classroom η, conditioned on the class having an infectious source case. Then, we multiplied η by the probability that a susceptible student attends a class with an infectious student, obtaining the unconditional probability of infection per class hour. Through a few linear approximations, we extrapolate the probability of infection in class over the semester to be roughly proportional to η, class size, campus prevalence, and the number of class hours per semester. The Simulation section in the Online Appendix further discusses the magnitude of the approximation errors.

Lastly, we generated a distributional estimate using 100,000 samples, with each sample representing the semester-wise risk associated with a specific parameter configuration drawn from the priors.

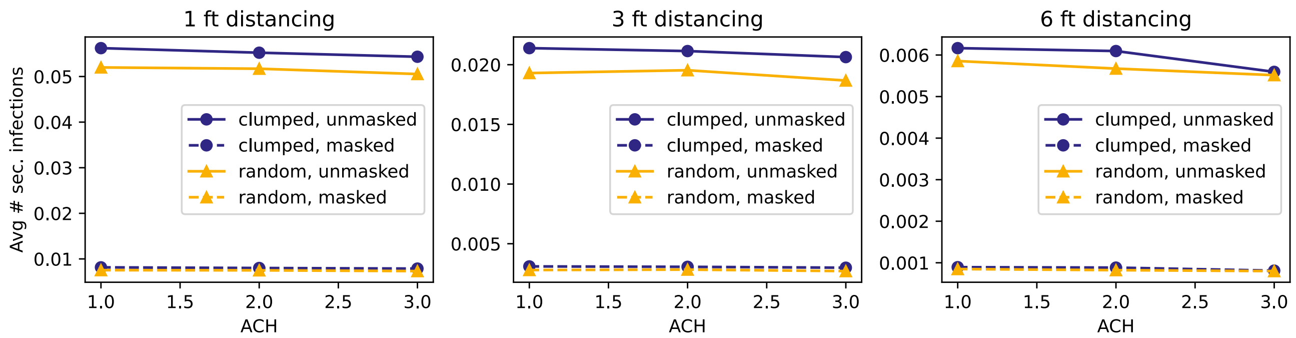
A similar procedure was applied to faculty and graduate student instructors. We assumed that the instructor is sufficiently distanced from the students so that risk only arises from transmission over long distances. We adjusted the unconditional probability of infection per hour of class to account for their population sizes relative to the undergraduate population size. We also assumed that the teaching load, proportional to the students' class hours, is divided between faculty and graduate student instructors at a two to one ratio.

Results and Recommendation for the Fall 2021 Semester

Here, we summarize the results and recommendations of our modeling analysis. Figure 5 and Table 3 present the expected number of secondary infections among 50 students, with 1 of them positive, during a one-hour lecture under different intervention combinations, assuming a 90% vaccination rate. Our model results showed that different seating policies and different ventilation conditions both resulted in comparable risk. Even though increasing distancing provided a large risk reduction, such benefit was deemed to be outweighed by logistical difficulty as well as reduction in class capacity. On the other hand, masking was much more effective than enforcing a fixed seating plan and increasing ventilation. Indeed, requiring masking in dense classrooms with unrestricted seating was easy to implement, incurred little logistical or financial cost, and allowed classes to be held at full capacity. The following analysis shows that this combination of interventions resulted in acceptable risk over the semester.

We next present the simulated distributions of infection risk for students and instructors. For students, we focused on undergraduates and assumed a total of 15,000. For instructors, we accounted for both faculty and graduate student instructors, with estimates of 850 faculty and 3,120 graduate student instructors (details are given in the Assumptions and Parameters section in the Online Appendix). Our estimated risk for undergraduates can be thought of as a representative upper

Figure 5. (Color online) Average Number of Secondary (Sec.) Infections Among 50 Students, 1 of Them Positive, over One Hour of Lecture for Different Intervention Settings Assuming a 90% Vaccination Rate



Notes. Lines with dots and triangles represent unrestricted and fixed seating, respectively. Solid and dashed lines represent 0% and 100% masking, respectively.

bound for all students, including graduate and professional ones. At Cornell, graduate students take either a similar number of classes as undergraduates (e.g., one-year masters and Masters of Business Administration students) or fewer classes (e.g., two-year masters and early-stage PhD students) if not none (late-stage PhD students). A small number of these classes may be shared by undergraduate and graduate students. As most infection spikes had occurred among undergraduates and the prevalence among graduate students was usually lower, the risk for undergraduates constituted a conservative estimate of the general risk for all students.

Student Classroom Risk

We projected that the median risk of infection per student because of lecture transmission in the fall of 2021 would be 0.5% at 90% vaccination rate. (An earlier version of this analysis (Cornell COVID-19 Modeling Team 2021a) predicted this number to be 0.4% owing to outdated parameters.) Figure 6 shows the estimated distribution of this risk across 100,000 simulated outcomes; the median is indicated by the red dashed line in Figure 6. The right tail of the estimated risk distribution in Figure 6 mainly results from the right tail of the lognormal prior over the prevalence parameter.

Instructor Classroom Risk

We projected that the median risk of infection per instructor because of lecture transmission in the fall of 2021 would be 0.02% for vaccinated faculty instructors and 0.003% for vaccinated graduate student instructors. The estimated distribution of risk across simulated outcomes is presented in Figures 7 and 8.

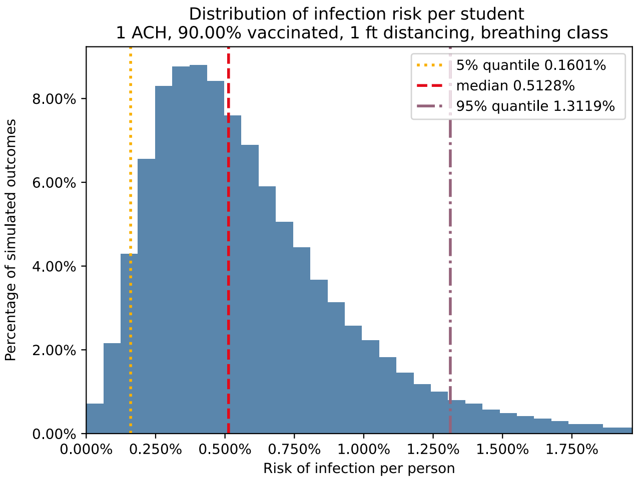
The risk was approximately doubled for an unvaccinated instructor. Because more than 99% of professorial faculty had been vaccinated by the start of the semester (Rosenberg 2021) and because those who chose not to be vaccinated would be highly cautious, we only show the estimated risk for the vaccinated instructors here.

The projected risk for instructors was much lower than that for students. This is mainly because of the modeling choice that instructors were not subject to short-distance transmission based on the natural distancing between instructors and students in classrooms.

Table 3. Average Number of Secondary Infections Among 50 Students, 1 of Them Positive, over One Hour of Lecture for Different Intervention Settings Assuming a 90% Vaccination Rate

Distancing and ventilation level	Unrestricted seating		Fixed seating	
	Unmasked	Masked	Unmasked	Masked
1-foot distancing				
1 ACH	5.62×10^{-2}	8.12×10^{-3}	5.20×10^{-2}	7.54×10^{-3}
2 ACH	5.52×10^{-2}	8.00×10^{-3}	5.17×10^{-2}	7.45×10^{-3}
3 ACH	5.43×10^{-2}	7.88×10^{-3}	5.05×10^{-2}	7.33×10^{-3}
3-foot distancing				
1 ACH	2.14×10^{-2}	3.10×10^{-3}	1.93×10^{-2}	2.80×10^{-3}
2 ACH	2.11×10^{-2}	3.07×10^{-3}	1.95×10^{-2}	2.83×10^{-3}
3 ACH	2.06×10^{-2}	2.99×10^{-3}	1.87×10^{-2}	2.71×10^{-3}
6-foot distancing				
1 ACH	6.17×10^{-3}	8.94×10^{-4}	5.86×10^{-3}	8.49×10^{-4}
2 ACH	6.10×10^{-3}	8.84×10^{-4}	5.67×10^{-3}	8.23×10^{-4}
3 ACH	5.60×10^{-3}	8.11×10^{-4}	5.52×10^{-3}	8.00×10^{-4}

Figure 6. (Color online) Distribution of Risk of Lecture Transmission for a Student Across the Entire Fall 2021 Semester over 10^5 Simulation Trials



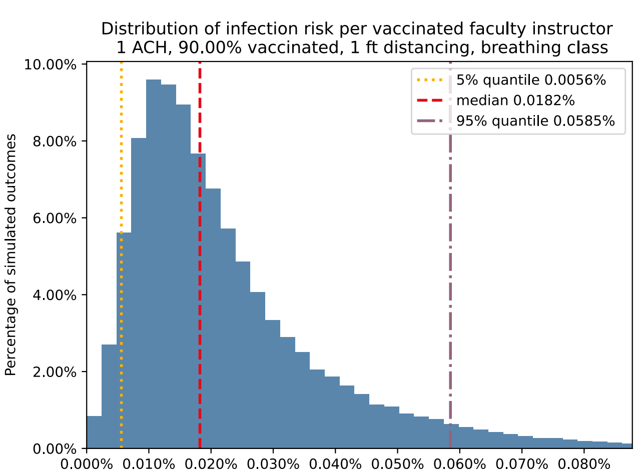
Notes. Median risk (the dashed line) is 0.51%. The 5% and 95% quantiles (the dotted and dotted-dashed lines, respectively) are 0.16% and 1.31%, respectively.

In addition, instructors spent less time in class over a semester compared with students.

Recommendations

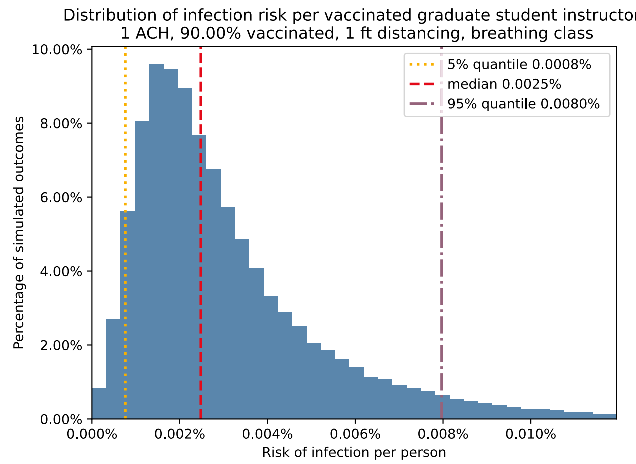
Based on our analysis, we believed that fully dense in-person classes, with masking enforced, could be safely implemented for the fall 2021 semester. We estimated the total risk of classroom transmission per student across the entire semester to be around 0.5% or roughly 1 in 200. For faculty and graduate students, the estimated risk of classroom transmission was even lower, roughly 1 in 5,000–40,000 across the entire semester. An individual's odds of being struck by lightning in life are on the order of 1 in 10,000 (National Weather Service 2019), which is comparable.

Figure 7. (Color online) Distribution of Risk of Lecture Transmission for a Vaccinated Faculty Instructor Across the Entire Fall 2021 Semester over 10^5 Simulation Trials



Notes. Median risk (the dashed line) is 0.018%. The 5% and 95% quantiles (the dotted and dotted-dashed lines, respectively) are 0.0056% and 0.059%, respectively.

Figure 8. (Color online) Distribution of Risk of Lecture Transmission for a Vaccinated Graduate Student Instructor Across the Entire Fall 2021 Semester over 10^5 Simulation Trials



Notes. Median risk (the dashed line) is 0.0025%. The 5% and 95% quantiles (the dotted and dotted-dashed lines, respectively) are 0.0008% and 0.008%, respectively.

Under the assumption that 15,000 students would return to Cornell University for the fall 2021 semester, we conservatively anticipated an additional 75 cases because of classroom transmission, with this figure rising to 119 under 90% masking compliance. We did not expect these additional cases to strain the testing and quarantine capacity of the university; Cornell's testing infrastructure was able to handle tens of thousands of tests per week, and it had the capacity to quarantine hundreds of students at a time. In addition, given the estimate of COVID-19 hospitalization rates for college-age students of 0.005% (Centers for Disease Control and Prevention 2021a), we did not expect that any students would be hospitalized from an infection because of classroom transmission. Finally, assuming that 850 faculty members and 3,120 graduate students serve as instructors in the fall 2021 semester, we did not expect to observe any instructor cases linked to classroom transmission.

Evaluation

To evaluate our modeling framework and recommendations, we retrospectively investigated COVID-19 cases from August 26, 2021 to December 7, 2021. A spike in cases occurred in early to mid-December because of the importation of the Omicron variant (Meredith et al. 2022). We exclude the peak from the plot for two reasons; it happened after the end of the instruction period when no classes were in session, and our modeling analyses and recommendations were specific to the Delta variant.

Student Transmission

We present the following body of evidence that minimal classroom transmission occurred among students during the fall 2021 semester (Cornell University 2021b).

1. When a student tested positive during the fall 2021 semester, Cornell tested all students attending the same class to the extent feasible. In addition, genetic sequencings of positive cases were compared to determine whether cases were related. These investigations did not yield evidence of classroom transmission.

2. We collected seating data for a class held in a lecture hall that contained more than 1,000 students. When a student in that class tested positive, we investigated to see whether any students seated near the infected student subsequently tested positive. Although these data are sparse, there were 20 instances of an infected student sitting within three seats of susceptible students. None of these cases were associated with a susceptible student testing positive.

3. Throughout the semester, the weeks with the highest rates of on-campus transmission corresponded to breaks when classes were not held. This is consistent with travel and social gatherings, rather than classes, driving COVID-19 transmission on campus as was also observed in previous semesters (Cornell COVID-19 Modeling Team 2021b). Figure 9 shows the daily count of new cases for undergraduate students. The outbreaks occurred right after students returned to campus from breaks.

4. Contact tracing revealed that most positive cases can be linked by social gatherings, cohabitation, or travel.

This collection of evidence strongly suggests that classroom transmission was rare during the Delta wave of the fall 2021 semester at Cornell University.

Instructor Transmission

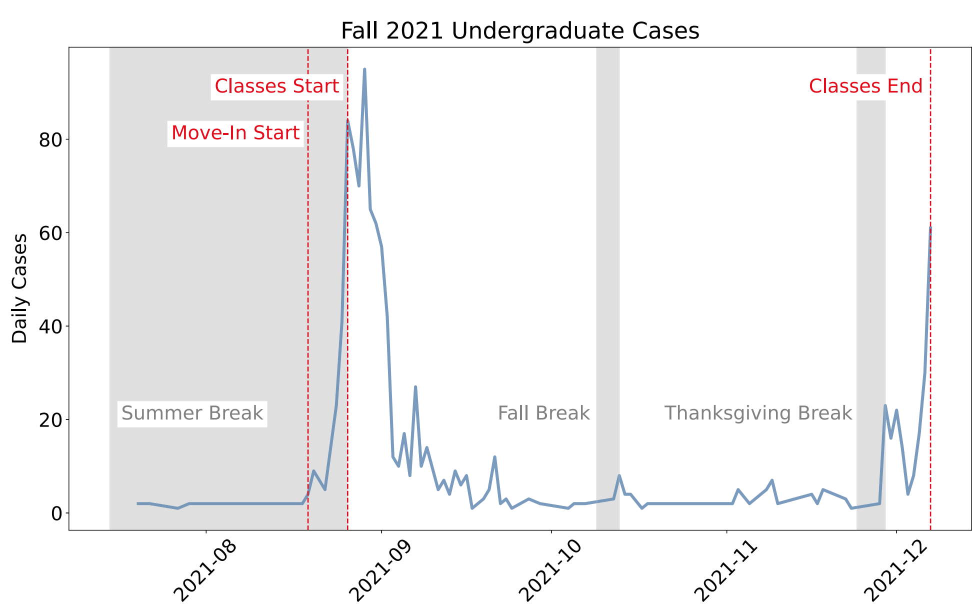
Throughout the fall 2021 semester, only a single faculty member tested positive for COVID-19 at Cornell. In addition, the prevalence of positive cases among graduate students was four times lower than the prevalence among undergraduate students. In all, infection rates among faculty and graduate students were much lower compared with those in the rest of the university population, which suggests that in-person teaching did not appreciably increase the risk of contracting COVID-19 during the fall 2021 semester relative to other sources of transmission.

Extensions

Beyond the Classroom

Although the main focus of our work was to model the risk of COVID-19 transmission in lectures and classrooms, we received many requests from the university administration to assess the risk of holding extracurricular events and gatherings during the fall

Figure 9. (Color online) Daily New Cases Among Undergraduate Students During the Fall 2021 Semester



Notes. The shaded intervals indicate school breaks (classes not in session). The largest spikes in cases occurred after events that involve significant student travel (the move-in period and Thanksgiving break). December 7 was the last day of classes for the semester. The Omicron variant was responsible for the rightmost spike in cases, which occurred after classes ended.

2021 semester. We were able to modify our modeling framework to accommodate these requests; we used the same model structure but updated our parameters to model eating, singing, socializing, and other events that occur in social gatherings. Our modeling analysis influenced the following decisions. For homecoming weekend, we determined that the homecoming football game and the Class of 2020s belated graduation ceremony were relatively low-risk events. However, we found that parties and festivities that occur after formal events incur substantially higher risk of COVID-19 transmission. As a result, we recommended canceling posthomecoming festivities, such as the fireworks and light shows on campus; these recommendations were accepted by the administration. We did not observe a large spike in cases on campus after homecoming weekend.

We were also asked by executive-level decision makers at Cornell University to assess the risk of the campus-sponsored Rosh Hashanah dinner. We determined that given the high vaccination rate on campus, this event would be safe to attend. Finally, we were asked to evaluate the risk of indoor physical education classes and music and choir classes. We modified our model to account for the increased aerosol emission because of these activities, and we determined that it was safe to hold these classes with dense seating configurations. No cases were linked to these courses at the end of the semester.

The flexibility of our framework in accommodating these ad hoc situations indicates that our framework can be applied to other industries besides higher education to plan indoor space use to avoid the transmission of infectious diseases across a range of applications.

Beyond COVID-19

In addition, by refitting the models on short-range and long-range transmission and by re-estimating the parameters on vaccine and mask efficacy, we can easily adapt our framework to model other respiratory diseases or COVID-19 variants. As such, our modeling framework can be used to assess infection risk in future pandemics across various settings.

Conclusion

Our modeling framework for COVID-19 transmission in classrooms allowed Cornell University to analyze the risk of holding in-person classes and compare the effectiveness of interventions. Using the recommendations provided by our modeling framework, Cornell was able to return to prepandemic levels of in-person instructions for the fall 2021 semester, improving the educational experience of students compared with previous semesters while ensuring safety. Post hoc analysis at the end of the semester confirmed that classroom transmission was rare and that teaching in-person classes was a low-risk activity. Finally, our modeling framework is flexible and can be adapted to model infection risk for respiratory diseases across a wide range of applications.

Acknowledgments

This work was conducted with support from Cornell University when the authors served on the Cornell COVID-19 Mathematical Modeling Team. Brian Liu and Yujia Zhang contributed equally to this work.

References

Adzic F, Roberts BM, Hathway EA, Matharu RK, Ciric L, Wild O, Cook M, Malki-Epshtein L (2022) A post-occupancy study of ventilation effectiveness from high-resolution CO_2 monitoring at live theatre events to mitigate airborne transmission of SARS-CoV-2. *Building Environ.* 223:109392.

American Society of Heating, Refrigerating and Air Conditioning Engineers (2002) ANSI-ASHRAE standard 129-1997 (RA 2002): Measuring air change effectiveness. Working paper, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Peachtree Corners, GA.

Andrews N, Stowe J, Kirsebom F, Toffa S, Rickeard T, Gallagher E, Gower C, et al. (2021) Effectiveness of COVID-19 vaccines against the Omicron (B. 1.1. 529) variant of concern. Preprint, submitted December 14, https://www.medrxiv.org/content/10.1101/2021.12.14.21267615v1.

Bazant MZ, Bush JW (2021) A guideline to limit indoor airborne transmission of COVID-19. *Proc. Natl. Acad. Sci. USA* 118(17): e2018995118.

Callaway E (2021) Delta coronavirus variant: Scientists brace for impact. *Nature* 595(7865):17–18.

Centers for Disease Control and Prevention (2021a) COVID-net: COVID-19-associated hospitalization surveillance network. Accessed August 21, 2022, https://gis.cdc.gov/grasp/covidnet/covid19_3.html.

Centers for Disease Control and Prevention (2021b) Scientific brief: SARS-CoV-2 transmission. Accessed April 20, 2024, https://archive.cdc.gov/#/details?url=https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/sars-cov-2-transmission.html.

Cheng VCC, Lung DC, Wong SC, Au AKW, Wang Q, Chen H, Xin L, et al. (2022) Outbreak investigation of airborne transmission of Omicron (B.1.1.529)-SARS-CoV-2 variant of concern in a restaurant: Implication for enhancement of indoor air dilution. *J. Hazardous Materials* 430:128504.

Ciotti M, Ciccozzi M, Pieri M, Bernardini S (2022) The COVID-19 pandemic: Viral variants and vaccine efficacy. *Critical Rev. Clinical Laboratory Sci.* 59(1):66–75.

Cipriano LE, Haddara WM, Zaric GS, Enns EA (2021) Impact of university re-opening on total community COVID-19 burden. *PLoS One* 16(8):e0255782.

Cornell COVID-19 Modeling Team (2021a) Analysis of fall 2021 classroom COVID-19 transmission. Accessed April 20, 2024, https://web.archive.org/web/20220611030537/https://covid.cornell.edu/_assets/files/classroom_analysis.pdf.

Cornell COVID-19 Modeling Team (2021b) Mathematical modeling for Cornell's spring semester. Accessed April 20, 2024, https://web.archive.org/web/20220611030559/https://covid.cornell.edu/_assets/files/general-audience-spring-modeling-20210216.pdf.

Cornell Faculty (2021) Letter to Provost Kotlikoff and Vice Provost Nishii. Accessed August 21, 2022, https://cornellsun.com/2021/08/29/guest-room-letter-to-provost-kotlikoff-and-vice-provost-nishii/.

Cornell University (2021a) COVID-19 faculty and staff town hall, August 11, 2021. Accessed August 21, 2022, https://www.

cornell.edu/video/covid-19-faculty-staff-town-hall-august-11-2021.

Cornell University (2021b) What is the university doing to track classroom transmission? Accessed April 20, 2024, https://web.archive.org/web/20211221180155/https://covid.cornell.edu/students/academic-policies/.

Cornell University COVID-19 Response (2021) End of semester guidance for instructors. Accessed April 20, 2024, https://web.archive.org/web/20211220054519/https://covid.cornell.edu/updates/20211211-end-semester-guidance.cfm.

Cornell University CTRO (2020) Committee on Teaching Reactivation Options (C-TRO). Accessed April 20, 2024, https://web.archive.org/web/20200930185057/https://covid.cornell.edu/_assets/files/ctro-final-report.pdf.

de Gier B, Andeweg S, Joosten R, Ter Schegget R, Smorenburg N, van de Kassteele J, Hahné SJ, van den Hof S, de Melker HE, Knol MJ (2021) Vaccine effectiveness against SARS-CoV-2 transmission and infections among household and other close contacts of confirmed cases, the Netherlands, February to May 2021. *Euro Surveillance* 26(31):2100640.

Dorn E, Hancock B, Sarakatsannis J, Viruleg E (2020) COVID-19 and student learning in the United States: The hurt could last a lifetime. Working paper, McKinsey & Company, New York.

Foster A, Kinzel M (2021) Estimating COVID-19 exposure in a classroom setting: A comparison between mathematical and numerical models. *Phys. Fluids (1994)* 33(2):021904.

Frazier PI, Cashore JM, Duan N, Henderson SG, Janmohamed A, Liu B, Shmoys DB, Wan J, Zhang Y (2022) Modeling for COVID-19 college reopening decisions: Cornell, a case study. *Proc. Natl. Acad. Sci. USA* 119(2):e2112532119.

Gore AB, Kurz ME, Saltzman MJ, Splitter B, Bridges WC, Calkin NJ (2022) Clemson University's rotational attendance plan during COVID-19. *INFORMS J. Appl. Analytics* 52(6):553–567.

Hekmati A, Luhar M, Krishnamachari B, Matarić M (2022) Simulating COVID-19 classroom transmission on a university campus. *Proc. Natl. Acad. Sci. USA* 119(22):e2116165119.

Hu M, Lin H, Wang J, Xu C, Tatem AJ, Meng B, Zhang X, et al. (2021) Risk of coronavirus disease 2019 transmission in train passengers: An epidemiological and modeling study. *Clinical Infectious Diseases* 72(4):604–610.

Israel Ministry of Health (2021) Vaccine efficacy. Accessed June 13, 2022, https://www.gov.il/BlobFolder/reports/vaccine-efficacy-safety-follow-up-committee/he/files_publications_corona_two-dose-vaccination-data.pdf.

Ji S, Xiao S, Wang H, Lei H (2022) Increasing contributions of airborne route in SARS-CoV-2 Omicron variant transmission compared with the ancestral strain. *Building Environ.* 221:109328.

Jimenez J, Peng Z (2024) COVID-19 aerosol transmission estimator. Accessed January 23, 2024, https://tinyurl.com/covid-estimator.

Johnson C, Wilson RL (2022) Practice summary: A multiobjective assignment model for optimal socially distanced classrooms for the Spears School of Business at Oklahoma State University. *INFORMS J. Appl. Analytics* 52(3):295–300.

Lee J, Solomon M, Stead T, Kwon B, Ganti L (2021) Impact of COVID-19 on the mental health of US college students. *BMC Psych.* 9(1):1–10.

Lieberwitz R (2021) Cornell AAUP chapter letter to President Pollack. Accessed August 21, 2022, https://cornellsun.com/2021/08/31/guest-room-cornell-aaup-chapter-letter-to-president-pollack/.

Lopez Bernal J, Andrews N, Gower C, Gallagher E, Simmons R, Thelwall S, Stowe J, et al. (2021) Effectiveness of Covid-19 vaccines against the B.1.617.2 (Delta) variant. *New England J. Medicine* 385(7):585–594.

Meredith GR, Diel DG, Frazier PI, Henderson SG, Koretzky GA, Wan J, Warnick LD (2022) Routine surveillance and vaccination on a university campus during the spread of the SARS-CoV-2 Omicron variant. *JAMA Network Open* 5(5):e2212906.

Mirzaei PA, Moshfeghi M, Motamedi H, Sheikhnejad Y, Bordbar H (2021) A simplified model to estimate COVID19 transport in enclosed spaces. *J. Phys. Conf. Ser.* 2069:012191.

Mittal R, Ni R, Seo JH (2020) The flow physics of COVID-19. *J. Fluid Mechanics* 894:F2.

Mohamadi F, Fazeli A (2022) A review on applications of CFD modeling in COVID-19 pandemic. *Arch. Comput. Methods Engrg.* 29(6):3567–3586.

National Weather Service (2019) How dangerous is lightning? Accessed June 13, 2022, https://www.weather.gov/safety/lightning-odds.

Navabi-Shirazi M, El Tonbari M, Boland N, Nazzal D, Steimle LN (2022) Multicriteria course mode selection and classroom assignment under sudden space scarcity. *Manufacturing Service Oper. Management* 24(6):3252–3268.

New York State Department of Health (2021a) Covid-19: Data on variants. Accessed June 13, 2022, https://coronavirus.health.ny.gov/covid-19-variant-data.

New York State Department of Health (2021b) Interim guidance for higher education during the COVID-19 public health emergency. Accessed March 8, 2023, https://www.governor.ny.gov/sites/default/files/atoms/files/Higher_Education_Detailed_Guidelines.pdf.

New York Times (2021) *NYTimes*/COVID-19-data: A repository of data on coronavirus cases and deaths in the U.S. https://github.com/nytimes/covid-19-data.

Patel K, Lee I (2022) Here's what the Ivy League is deciding for fall 2020. Accessed December 12, 2022, https://www.thedp.com/article/2020/04/penn-ivy-league-fall-semester-2020-coronavirus.

Payne A (2020) College towns feel financial impact of pandemic. Accessed October 31, 2022, https://wfpl.org/college-towns-feel-financial-impact-of-pandemic/.

Polack FP, Thomas SJ, Kitchin N, Absalon J, Gurtman A, Lockhart S, Perez JL, et al. (2020) Safety and efficacy of the BNT162b2 mRNA Covid-19 vaccine. *New England J. Medicine* 383(27):2603–2615.

Public Health Ontario (2022) COVID-19 transmission through short and long-range respiratory particles. Accessed April 20, 2024, https://www.publichealthontario.ca/-/media/Documents/nCoV/phm/2022/01/covid-19-respiratory-transmission-range.pdf?sc_lang=en.

Rosenberg M (2020a) Most courses will be taught online this spring. Here's how Cornell decided the roster. Accessed November 1, 2022, https://cornellsun.com/2020/12/10/most-cornell-courses-will-be-taught-online-this-spring-heres-how-cornell-decided-the-roster/.

Rosenberg M (2020b) Three-quarters of enrolled students are zooming from Ithaca this fall. Accessed October 31, 2022, https://cornellsun.com/2020/11/08/three-quarters-of-enrolled-students-are-zooming-from-ithaca-this-fall/.

Rosenberg M (2021) Vaccination, testing, masking: Here's what you need to know for fall 2021. Accessed August 28, 2022, https://cornellsun.com/2021/08/16/vaccination-testing-masking-heres-what-you-need-to-know-for-fall-2021/.

Schijven J, Vermeulen LC, Swart A, Meijer A, Duizer E, de Roda Husman AM (2021) Quantitative microbial risk assessment for airborne transmission of SARS-CoV-2 via breathing, speaking, singing, coughing, and sneezing. *Environ. Health Perspect.* 129(4):047002.

Srivastava M, Rosenberg M (2020) Two-thirds of Cornell classes are online, despite hybrid semester. Accessed November 1, 2022, https://cornellsun.com/2020/09/06/two-thirds-of-cornell-classes-are-online-despite-hybrid-semester/.

Stanford University (2021) COVID-19 update and new protocols. Accessed November 1, 2022, https://healthalerts.stanford.edu/covid-19/2021/09/02/covid-19-update-and-new-protocols/.

Sullivan R (2020) College towns and COVID-19: The impact on New England. Working paper, Federal Reserve Bank of Boston, Boston.

Tareq AM, Emran TB, Dhama K, Dhawan M, Tallei TE (2021) Impact of SARS-CoV-2 Delta variant (B. 1.617. 2) in surging second wave of COVID-19 and efficacy of vaccines in tackling the ongoing pandemic. *Human Vaccines Immunotherapy* 17(11): 4126–4127.

Walke HT, Honein MA, Redfield RR (2020) Preventing and responding to COVID-19 on college campuses. *J. Amer. Medical Assoc.* 324(17):1727–1728.

Wan J, Cazer CL, Clarkberg ME, Henderson SG, Lee SE, Meredith GR, Osman M, Shmoys DB, Frazier PI (2023) Booster vaccination protection against SARS-CoV-2 infections in young adults during an Omicron BA.1-predominant period: A retrospective cohort study. *PLoS Medicine* 20(1):e1004153.

Washington NL, Gangavarapu K, Zeller M, Bolze A, Cirulli ET, Schiabor Barrett KM, Larsen BB, et al. (2021) Emergence and rapid transmission of SARS-CoV-2 B.1.1.7 in the United States. *Cell* 184(10):2587–2594.e7.

Watanabe T, Bartrand TA, Weir MH, Omura T, Haas CN (2010) Development of a dose-response model for SARS coronavirus. *Risk Anal.* 30(7):1129–1138.

Verification Letter

Michael I. Kotlikoff, Provost and Professor of Molecular Physiology; Tim Fitzpatrick, Senior Director, Environment, Health and Safety; Lisa H. Nishii, Vice Provost for Undergraduate Education; and Gary Koretzky, Professor, Department of Microbiology & Immunology, Office of the Provost, Cornell University, 300 Day Hall, Ithaca, NY 14853-2801, write:

"This letter verifies the extensive collaboration between the university and the Cornell COVID-19 Modeling Team described in the article 'Modeling the Risk of In-Person Instruction During the Coronavirus Disease 2019 Pandemic' submitted to the *INFORMS Journal on Applied Analytics*. The work presented in the paper was part of a much larger collaboration to ensure campus safety during the COVID-19 pandemic while executing the university's mission to provide high-quality instruction to students. Determining the best strategy to operate classrooms during the pandemic was a significant challenge at Cornell University. We needed to ensure safety but also wanted to provide the highest quality educational experience possible while simultaneously satisfying operational constraints. As we planned for our Fall 2020 semester, public health guidance from the CDC and our local health department told us that we could ensure safety in classrooms through six-foot social distancing between occupied seats and by requiring masks. We additionally believed safety could be further supported by retrofitting some classrooms with HVAC to improve their ventilation and excluding from use other classrooms that had less air circulation.

We thought that classrooms might still be safe even with fewer interventions, but we weren't sure—given the novelty and complexity of the situation, it was extremely difficult for us to know the relative impact of each intervention on pandemic safety. Because safety was paramount and because of our uncertainty, we used this full set of interventions in Fall of 2020 and Spring of 2021. Unfortunately, as a consequence, many classes had too many students to be accommodated with an in-person classroom experience. While we would have preferred to have all students be able to attend class in person, many instructors were asked to teach in a hybrid format where some students attended in person and others attended over Zoom. This was difficult for both our instructors and our students, as teaching and learning in a hybrid format are substantially more difficult than doing so in person. There was also significant operational overhead and energy costs associated with enhanced ventilation.

For the Fall of 2021, we turned for help to the Cornell Mathematical Modeling Team, members of which wrote the article submitted here to *IJAA*. They had been working with us on a broader collection of analytical and modeling questions to help the university respond to the pandemic. As we planned for that semester, we knew that much of the Cornell community would be vaccinated by its start. We thought this might open a window to be able to safely use all classrooms and to fill them at a greater density, providing the space for all students to attend class in person. We were unsure, however, as safety remained paramount and the Delta variant had recently emerged in the summer of 2021 with increased infectivity and vaccine resistance. Adding to the challenge of making the right decision, different stakeholders (students, instructors, and administrators) had strong but conflicting opinions about the right course of action. The Cornell Mathematical Modeling Team provided immense value by developing a mathematical model to answer these questions by estimating the risk of infection and how it varied with the interventions applied, campus prevalence, and vaccination rates. This is the model described in this article. Based on this analysis, we were confident that fully dense in-person classes using all existing classrooms would be safe if students, faculty, and staff were vaccinated and wore masks in class. As a result, we decided to offer our full slate of courses in-person in Fall 2021, which increased the number of fully in-person classes offered fivefold compared with Spring 2021. The modeling results were also shared with all of the other Ivy-Plus universities, informing their individual policies.

As the semester unfolded, contact tracing and other investigations did not reveal any COVID-19 cases associated with classroom transmission during the Fall 2021 semester. Thus, reality unfolded the way that the analysis in this article said it would; in-person classroom instruction is safe under the interventions recommended by this analysis and under the viral prevalence and vaccination rates present at the time. In addition to their help in supporting this critical decision, we appreciated the modeling team's dedication to transparency and rigor in communicating their modeling approach. They posted detailed write-ups of their analyses on the Cornell COVID-19 Response website, reassuring the Cornell community that the Fall 2021 semester would be safe. In addition, modeling team members were on hand during community town halls to address concerns from students, faculty, and staff on participating in in-person instruction. These combined efforts provided much clarity and reassurance regarding the University's COVID-19 guidelines during the confusing onset of the Delta wave of the pandemic.

Finally, the modeling team was able to adapt their framework to assess the safety of other university events throughout the semester, such as homecoming, concerts, holiday events, sporting events, and graduation. The analysis provided by the team influenced our decisions at the executive level on what events and functions to hold. We believe that given the team's modeling success at Cornell, the work presented in "Modeling the Risk of In-Person Instruction During the Coronavirus Disease 2019 Pandemic" would be of great interest to other universities nationwide and would serve as a useful guide toward reopening indoor events during pandemics."

Brian Liu is a PhD candidate in operations research at Massachusetts Institute of Technology. His research interests include interpretable machine learning, discrete optimization, and statistics.

Yujia Zhang holds a PhD in applied mathematics from Cornell University. Her research interests include epidemic modeling and simulation, group testing, and Bayesian optimization.

Shane G. Henderson holds the Charles W. Lake, Jr. Chair in Productivity in the School of Operations Research and Information Engineering at Cornell University. His research interests include discrete-event simulation, simulation optimization, emergency services planning, and transportation. He is an INFORMS Fellow and a corecipient of the INFORMS Wagner Prize for his work on bike-sharing programs.

David B. Shmoys is the Laibe/Acheson Professor in the School of Operations Research and Information Engineering and the Department of Computer Science as well as the founding director of the Center for Data Science for Enterprise & Society at Cornell University. His research interests are in the design and analysis of optimization models and algorithms for a broad cross-section of decision-making settings.

Peter I. Frazier is the Eleanor and Howard Morgan Professor of Operations Research and Information Engineering at Cornell University and a Senior Staff Scientist at Uber. His research connects machine learning and operations research, including Bayesian optimization and multiarmed bandits. During the pandemic, he led the Cornell COVID-19 Mathematical Modeling Team, which helped design Cornell's asymptomatic testing program and provided university leadership with science-based decision support.