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SARS-CoV-2 aerosol risk models for the Airplane Seating Assignment Problem

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A R T I C L E I N F O

Keywords:
- Public health
- Air travel
- COVID-19
- Discrete optimization

A B S T R A C T

Transmission of SARS-CoV-2 between passengers on airplanes is a significant concern and reducing the transmission of SARS-CoV-2 or other viruses aboard aircraft could save lives. Solving the Airplane Seating Assignment Problem (ASAP) produces seating arrangements that minimize transmission risks between passengers aboard an aircraft, but the chosen risk model affects the optimal seating arrangement. We analyze previous risk models and introduce two new risk models, masked and unmasked, based on previous experiments performed aboard real aircraft to test aerosol dispersion of SARS-CoV-2 sized particles. We make recommendations on when each risk model is applicable and the types of seating arrangements that are optimal for each risk model.

1. Introduction

SARS-CoV-2, the virus that causes COVID-19, has caused over three million deaths worldwide and is continuing to kill nearly 50,000 people per week as of 14 November 2021 (World Health Organization, 2021). SARS-CoV-2 was first detected as cases of pneumonia with an unknown cause in December 2019 in Wuhan, China and then identified as a new type of coronavirus on 7 January 2020 (World Health Organization, 2020a). The virus rapidly spread and by the end of January 2020 had reached Southeast Asia, Australia, Europe, and North America, with almost 10,000 cases in China and more than 100 confirmed cases across 19 countries outside of China (World Health Organization, 2020b).

Some people confirmed to be infected with SARS-CoV-2 are completely asymptomatic while they are able to spread the disease to others for long periods of time (Long et al., 2020; Oran and Topol, 2020). This makes it more difficult to detect infectious passengers as they board international flights, leading to those passengers spreading the disease after arriving at their destination. Furthermore, in-flight transmission of SARS-CoV-2 has been confirmed on multiple international flights (Freedman and Wilder-Smith, 2020), which makes contact tracing the newly infected passengers on the airplane difficult as those passengers pass through multiple connecting flights.

There are many different seating arrangements for a plane that is partially full, such as pushing everyone to the front, letting passengers space themselves out, or blocking middle seats. Given a plane full of passengers, some of which are infected with SARS-CoV-2, some seating arrangements will have a lower risk of creating secondary infections. Pavlik et al. (2021) presents the Airplane Seating Assignment Problem (ASAP) with the goal of minimizing the total transmission risk between passengers by placing passengers into an optimal seating configuration.

The optimal seating arrangement for ASAP depends critically on the input risk model, which assigns relative risk scores to pairs of passengers based on their seat positions on the assumption that either passenger could infect the other. This paper extends Pavlik et al. (2021) by introducing two new risk models based on recent aerosol dispersion tests with and without passengers wearing surgical masks (Silcott et al., 2020). ASAP seating arrangements are compared under the different risk models to make recommendations.

Transmission risk models depend on the possible modes of transmission. SARS-CoV-2 can be transmitted by droplets, contact, fecal-oral, and airborne modes (Delikhoon et al., 2021). Droplets are particles generated during breathing, talking, and coughing that can infect another person if they reach their mouth, nose, or eyes. Contact transmission...
occurs when a person touches an object that contains particles of the virus; it includes both direct contact, such as shaking hands, and fomite transmission, such as touching a surface contaminated with virus particles (Centers for Disease Control, 2021b). Fecal-oral transmission occurs when any fecal matter from an infectious person is ingested, such as from a contaminated water supply. Airborne transmission occurs from droplets that are small enough to stay suspended in the air instead of falling to the ground. ASAP minimizes the risks of transmission between seated passengers during a flight and does not include risks when the passengers board or deboard the airplane (Milne et al., 2021). Therefore, we are concerned primarily with droplet and airborne transmission modes for SARS-CoV-2 transmission risk models aboard aircraft.

If masks are being worn, then the type of mask also has a significant impact on the risk models for ASAP. As of January 21, 2021, masks in compliance with Centers for Disease Control and Prevention (CDC) guidelines are required to be worn on all commercial aircraft in the United States (Biden, 2021). A compliant mask is essentially a cloth mask of two or more layers that completely covers the nose and mouth (Centers for Disease Control, 2021a). Cloth mask efficacy varies significantly depending on material choice and fit, but they are generally effective at blocking large respiratory droplets by providing a mechanical barrier (Sharma et al., 2020; Konda et al., 2020). Given the effectiveness of cloth masks and current wear guidelines, risk models based on data collected with masks worn should be used for ASAP.

Once a risk model has been selected, ASAP can be solved by using the Vertex Packing Risk minimization (VPR) and Risk-Constrained Vertex packing (RCV) mixed-integer linear programming models (Pavlik et al., 2021). Both models require an input graph representing the airplane layout with pairwise risk scores between seats, which are determined by the chosen risk model. VPR fixes the number of passengers and finds a seating arrangement that minimizes total risk, and RCV fixes a maximum total risk and finds a seating arrangement with as many passengers as possible. Both models can be solved using an off-the-shelf commercial solver such as CPLEX.

One notable limitation of both VPR and RCV for solving ASAP is that they assume all passengers are indistinguishable; nothing specific is known about any individual passengers. Every passenger should have an equal chance of being infectious and can possibly infect any other passenger. If those assumptions are not true, for example, if some passengers are from the same family and therefore have different risks relative to each other than to other passengers, then the total risks computed by VPR and RCV may not accurately reflect real-world transmission risks. Further research is needed to develop heterogeneous risk models that could be applied to such instances.

The paper is organized as follows. Section 2 analyzes the risk models that define which seats are considered high-risk relative to an index passenger. Section 3 examines the seating arrangements produced by each of the risk models on two representative airplanes (capacities 124 and 289). Section 4 provides recommendations about risk model selection, summarizes seating guidelines for each risk model, and suggests further experimentation or modeling to refine risk models.

### 2. Risk models

The risk models used to solve ASAP in Pavlik et al. (2021) are the coughing and non-coughing risk models. Both models are based on studies of influenza transmission and assume the passengers are not wearing any type of mask.

The coughing model assumes that each infectious passenger has coughing symptoms and no mask, which places the greatest risk on the seat directly in front of each passenger based on modeling and experimental results from Wan et al. (2009). The data and assumptions used for the coughing model include 3 h of exposure time and both airborne (<5 μm) and droplet (>5 μm) transmission modes. Fig. 1(a) shows the relative risk of placing a passenger in each seat near an index passenger in the center, with darker colors having more risk. The index passenger is the first infectious passenger from which other passengers may become infected.

The non-coughing model is simpler, assigning an identical risk factor (0.9) for each nearby seat within two seats to the left/right and one row forward/backward, as shown in Fig. 1(b). The non-coughing model is taken from data in Hertzberg et al. (2018) based on observation of passenger movement aboard transcontinental flights.

If wearing masks reduces risk uniformly, then optimal seating arrangements for the coughing and non-coughing risk models remain optimal after adding masks. But the assumption that masks reduce risk uniformly is likely unrealistic. For example, surgical masks have open sides which may redirect air flow when exhaling, whereas properly fitting N95 masks seal the nose and mouth completely and should prevent large droplets from escaping or being inhaled. The potentially nonuniform impact of wearing masks suggests the need for a new risk model based on experiments with masks. Recently, Silcott et al. (2020) tested in-flight aerosol dispersion of 1–3 μm particles in Boeing 777–200 and 767–300 airframes, with and without surgical masks. We use their data to create two new risk models, masked and unmasked, for use with ASAP. Data for the new SARS-CoV-2 vaccines was not available and the vaccines are not factored into any of the models.

Silcott et al. (2020) make several assumptions about SARS-CoV-2 parameters, so they emphasize their model is not a definitive SARS-CoV-2 transmission risk model. However, their results may still be useful for determining relative risk between different seating arrangements by assuming particle concentrations are a proxy for risk. The minimum risk seating arrangement does not change if the real risk of infection is uniformly higher or lower. For example, if the assumed viral production rates and infectious dose are wrong, then the number of expected transmissions would change but the seating arrangement would be the same.

The experiments of Silcott et al. (2020) are limited to airborne particles only, primarily the particles of the size generated by breathing, and do not include transmission by droplets, contact, or any other modes of transmission, and hence these models based on their results have the same limitations.

Their aerosol dispersion patterns on the Boeing 777–200 show that for infectious passengers in the rear sections of the aircraft, AFT and MID-AFT, the most dangerous seats are the seats next to the infectious passenger and the rows behind the infectious passenger. However, the row direction flips for the FWD and FWD-MID sections, such that the rows forward of the infectious passenger receive more aerosol particulates than the row behind. These location-dependent aerosol dispersion patterns indicate the airflow throughout the airplane is nonuniform. However, directional changes in relative risk do not present a significant issue for ASAP risk models. Risks in ASAP are inherently bidirectional because every passenger is considered potentially infectious and capable of transmitting to every other passenger. A single bidirectional risk value between a pair of seats represents the sum of the two directional transmission risks, i.e., the risk of seat a infecting seat b plus the risk of seat b infecting seat a. Hence non-uniform airflow does not change the seating arrangements generated by solving ASAP.

![Fig. 1](graphic.png) Fig. 1. Graphic demonstration of the risks of each model assuming one index passenger. A dotted pattern indicates the index passenger and darker colors indicate higher risk.
The unmasked model, based on grouping and averaging the risk values from the in-flight breathing with no mask experiments from Silcott et al. (2020) is

\[
\begin{align*}
0.0222 & \quad \text{if } u \text{ is directly beside } v \text{ or vice versa} \\
0.0069 & \quad \text{if } u \text{ is diagonally adjacent to } v \text{ or vice versa} \\
0.0058 & \quad \text{if } u \text{ is directly behind } v \text{ or vice versa} \\
0.0041 & \quad \text{if } u \text{ is in the same row as } v \text{ and not directly beside} \\
0.0039 & \quad \text{if } u \text{ is within two rows of } v \text{ and not adjacent or in the same row} \\
0 & \quad \text{otherwise.}
\end{align*}
\]

The masked model, based on grouping and averaging the risk values from the in-flight breathing with surgical mask experiments from Silcott et al. (2020) is

\[
\begin{align*}
0.0139 & \quad \text{if } u \text{ is directly beside } v \text{ or vice versa} \\
0.0060 & \quad \text{if } u \text{ is diagonally adjacent to } v \text{ or vice versa} \\
0.0049 & \quad \text{if } u \text{ is directly behind } v \text{ or vice versa} \\
0.0019 & \quad \text{if } u \text{ is in the same row as } v \text{ and not directly beside} \\
0.0030 & \quad \text{if } u \text{ is within two rows of } v \text{ and not adjacent or in the same row} \\
0 & \quad \text{otherwise.}
\end{align*}
\]

Risk for both models is based on the measured cumulative aerosol particles as a proxy for relative risk instead of estimating actual risk. A single risk value has no meaning by itself; it is only intended to be used to compare against other risk values to determine which seating configuration has a higher or lower risk. The tests for three rows or more from the index passenger were limited, and usually resulted in less than 0.0010 risk on the tests that did occur. Therefore, those risks were rounded down to zero.

The masked and unmasked risk models derived from Silcott et al. (2020) reveal masks do not uniformly reduce the risk of the unmasked model; rather, masks reduce the side-to-side risk more than the front-to-back risk. When sitting directly in front of an index passenger, a surgical mask has a 16% reduction in risk (from airborne particles generated by breathing, not including large droplets), but the same mask has a larger 37% reduction in risk for sitting immediately next to the index passenger. Similarly, a mask has a 23% reduction in risk for passengers within two rows, but a 54% reduction in risk for passengers in the same row and more than one seat away. This makes being two rows away the least risky non-zero category without a mask, but the larger reduction in risk makes the same row the least risky category in the masked model.

Fig. 2 illustrates the unmasked and masked risk models, showing the approximate risk level for each nearby passenger relative to an index passenger seated in the middle. The colors are normalized such that the highest risk, on the unmasked side-to-side adjacent seats, is pure black and zero risk is pure white. The seats shaded darker have more risk than the lighter shaded seats. In both models, the seats with greatest risk (i.e., darkest shading) are adjacent to the index passenger. The second risk tier includes the four diagonals, and the third risk tier comprises the seats in front of and behind the index passenger.

3. Seating assignment results

The masked and unmasked risk models are tested using VPR to generate minimum risk seating arrangements for a given number of passengers. Fig. 3 compares the seating charts generated by each risk model on a Boeing 737–700, each with 60 passengers out of a total capacity of 124. Fig. 4 is similar, showing seating charts on a Boeing 777-200LR, with 180 passengers out of 289 seats.

As can be seen in Figs. 3(a), 3(b), 4(a), and 4(b), both models produce similar seating arrangements by avoiding middle seats because they consider seating passengers side by side to carry the highest risk. The unmasked model is less strict about front/back spacing and is more likely to place passengers in separate rows while the masked model is more likely to put passengers in the same row. As the number of passengers increases, the options become more limited and both models converge on avoiding placing passengers next to each other as much as possible. However, wearing masks generates less cumulative risk: For 60 passengers, the minimal total risk score for the masked model is 1.83, nearly a 30% reduction compared to the minimal total risk score for the unmasked model (2.59). Note the reduction in risk is based on airborne transmission data and does not include larger droplet transmission. Also note that at 60 passengers, the plane is approximately half-full, and the optimal seating arrangements space passengers by keeping middle seats empty and skipping some rows.

The observed tendency to keep middle seats open when using the unmasked model aligns with a previous study of the impact of keeping middle seats open. Dietrich et al. (2021) simulates aerosol dispersion in a three-row section of an aircraft cabin with and without middle seats occupied, assuming no masks worn, and estimate a 57% reduction in SARS-CoV-2 exposure by emptying middle seats. For comparison, the unmasked risk model, when run on a Boeing 737–700, estimates a larger 67% reduction in risk by emptying the middle seats and reducing the number of passengers from 124 to 80.
One advantage of finding a seating assignment computationally, as opposed to using a rule of thumb like blocking the middle seats, is that the solver finds the optimal configuration even when the seat pattern is broken. At the rear of the 777-200LR cabin, the body narrows, eliminating a few seats, and the back of the middle section has two side lavatories that replace some seats. Using VPR to solve ASAP accounts for these disruptions to find a minimum risk configuration for the seats. Fig. 5 shows the seating arrangements for a 777-200LR when using the previously published coughing and non-coughing risk models (Pavlik et al., 2021) so they can be compared against Fig. 4. The actual risk values produced by each seating arrangement are not comparable because they use different sources of data with different scaling values, but the seating arrangements produced by using each risk model can be compared to see the differences in the patterns.

The coughing model assumes most of the risk is from uncontrolled coughs landing on the person in front, so it avoids that scenario as much as possible. The non-coughing model puts the same risk on a person one row forward and two seats left as it does on a person sitting directly beside, so it ends up creating clusters with a row spacing them apart. Much like the masked and unmasked are two different models that converge on a common behavior of generally blocking the middle seats, the coughing and non-coughing models converge on filling alternating rows.

Fig. 6 shows how the total risk score increases with passenger count under the unmasked and masked risk models on a Boeing 737–700. At small passenger counts, the risk is small, as few passengers are near enough to each other to create any risk. As the plane fills, more passengers are forced closer together, and the risk accumulation...
Fig. 6. Relative cumulative risk for each number of passengers, up to 124 passengers.

Fig. 7. Relative cumulative risk for each number of passengers, up to 80 passengers, showing the extra risk from blocking middle seats instead of solving for an optimal seating arrangement.

accelerates. As the passenger count approaches capacity, the available options decrease until the only solution is filling every seat.

The unmasked risk always increases faster than the masked risk, even for the 1–3 μm airborne particles that are exclusively considered under both models. For the first eight passengers both models produce seating arrangements with a total risk score of zero, because every passenger can be spaced with at least two empty rows between them. Above eight passengers, the masked model always achieves a lesser total risk score than the unmasked model. At nine passengers the unmasked vs masked risk is .0078 vs .0040, small in total risk but a 49% reduction for using the masks. With the plane completely full, the unmasked risk is 16.6 whereas the masked risk is 12.1, a 27% reduction in risk.

The cabin layout and discrete categories of risk types create phases of increasing risk, where each person added during a phase adds approximately the same amount of risk because they are part of a repeating pattern that is filling the aircraft. The phase ends when that pattern cannot continue because the plane has reached capacity under that pattern, and the risk added by the next person is usually much larger. Each phase change causes the minimum total risk score plot to get steeper, as shown in Fig. 6. The passenger count range for each phase depends on the seating arrangement categories in the risk model and the seating configuration of the plane. A phase can be as short as a single passenger but is usually three to eight passengers for the unmasked and masked models on the Boeing 737–700 aircraft.

Fig. 7 compares the difference between blocking all the middle seats (except rows with only two seats per side, where the aisle seat is blocked instead) or using any seat for up to 80 passengers out of the total of 124 on a Boeing 737–700. The graph stops at 80 because 80 is the maximum number of passengers that can be seated with the middle seats blocked, such that no passengers are sitting next to each other.

At 80 passengers the difference between blocking the middle seats and using an optimum seating configuration from VPR is a 5% reduction in risk, 3.84 vs 4.04 total risk scores.

The optimum seating arrangement for 80 passengers with 3.84 risk is shown in Fig. 8(a) and can be compared against the completely filled seating arrangement when the middle seats were removed with 4.04 risk in Fig. 8(b). The difference is that the VPR seating arrangement puts passengers side by side in the front section and rearmost row where there are fewer adjacencies. This allows a row near the back to be skipped, creating space between those six rearmost passengers and the rest of the plane.

4. Recommendations

All the risk models are based on respiratory diseases like influenza or COVID-19. The masked risk model is the only model that incorporates masks in the experiments that generated the data for the model and is likely the most accurate model so far for relative SARS-CoV-2 transmission risk aboard aircraft when passengers are wearing masks. The masked risk model does not specify any actual risks of transmission, it only represents relative risk between the different nearby seats, so it should only be used for seating arrangements and not for determining risks of infection.

The coughing risk model is most applicable for diseases that present with coughing or sneezing symptoms and the passengers are not wearing masks or covering their mouths when they cough. The primary risk in that model is from infectious passengers coughing droplets onto the person in front of them, with much smaller risks from droplets and airborne particles to the other people around the infectious passenger. If the coughing risk model applies, then the seating results suggest that skipping rows is the best strategy for minimizing risk instead of blocking middle seats.

The non-coughing risk model is a generalized neighbor risk. Any passenger too close to an infectious passenger, roughly within a six-foot social distancing radius, has a fixed amount of risk, but the risk does not depend otherwise on the distance. There is no difference in risk between being at the minimum and maximum range of risk. The
non-coughing risk model also converges on alternating rows as its risk minimization strategy, like the coughing model. The masked and unmasked risk models presented in this paper are for diseases that are transmitted via airborne particles 1–3 μm in size. The masked model assumes all the passengers are wearing surgical masks that catch larger droplets but still allow for reduced airborne transmission of small particles. Both the masked and unmasked model implicitly block middle seats because the greatest risk comes from seating passengers next to each other. Therefore, blocking the middle seat is a good guideline when airborne transmission of 1–3 μm aerosols is the primary concern, assuming an optimal seating layout from ASAP is not available.

Regardless of whether an alternating rows or blocked middle seats overall strategy is used, passengers should be spaced as far apart as possible. Fig. 9 shows seating arrangements at 1/4, 1/2, and 3/4 full, to demonstrate various levels of spacing.

More risk models can be produced with more experimental data or modeling, either to model the relative risks more accurately for a given respiratory disease based on its mode of transmission or to model the risks of a given environment. For example, the coughing model, which includes both droplet and airborne transmission, may not apply to diseases with only droplet transmission or when passengers wear masks that impede droplet transmission.

The seating arrangements produced by ASAP with VPR or RCV are only as accurate as the risk models that are used. Ideally, a risk model should be customized for the specific environment and transmissible disease. In the perfect case, every pair of seats aboard an aircraft can be assigned its own risk value using modeling and experimental data on that specific aircraft’s layout and environmental control system, instead of using more generic models based on relative positioning like the masked and unmasked models.

Acknowledgments

We would like to thank the Editor in Chief and the anonymous reviewers for their comments that resulted in a significantly improved manuscript.

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We would like to thank the Editor in Chief and the anonymous reviewers for their comments that resulted in a significantly improved manuscript.