



Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



Probability and estimated risk of SARS-CoV-2 transmission in the air travel system

Jenna K. Pang^{a,*}, Stephen P. Jones^a, Lindsay L. Waite^a, Nels A. Olson^a, Jason W. Armstrong^b, Robert J. Atmur^a, Joshua J. Cummins^a

^a The Boeing Company, USA

^b Boeing Defence Australia

ARTICLE INFO

Keywords:

COVID-19
Emerging communicable diseases
Risk
Epidemiology

ABSTRACT

Background: As an emerging virus, SARS-CoV-2 and the risk of transmission during air travel is of high interest. This paper is a retrospective estimate of the probability of an infectious passenger in the air travel system transmitting the SARS-CoV-2 virus to a fellow passenger.

Methods: Literature was reviewed from May–September 2020 to identify COVID-19 cases related to air travel. The studies were limited to publicly available literature for passengers; studies of flight crews were not reviewed. A novel quantitative approach was developed to estimate air travel transmission risk that considers secondary cases, the overall passenger population, and correction factors for asymptomatic transmission and underreporting.

Results: There were at least 2866 index infectious passengers documented to have passed through the air travel system in a 1.4 billion passenger population. Using correction factors, the global risk of transmission during air travel is estimated at 1:1.7 million; acknowledging that assumptions exist around case detection rate and mass screenings. Uncertainty in the correction factors and a 95% credible interval indicate risk ranges from 1 case for every 712,000 travelers to 1 case for every 8 million travelers.

Conclusion: The risk of COVID-19 transmission on an aircraft is low, even with infectious persons onboard.

1. Introduction

In late 2019, an outbreak of a novel coronavirus disease, now known to be caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus and named coronavirus Disease 2019 (COVID-19), was first documented in Wuhan, China [1]. By January 2020, the disease was confirmed to have spread to other parts of Asia [2], and by February 2020 cases were being seen around the globe [3]. The World Health Organization (WHO) declared the global outbreak a pandemic on March 11, 2020 [1]. As the pandemic continued, the air travel industry was severely impacted with a nearly 95% drop from 2019 passenger levels in a matter of weeks [4]. With segments of the global population continuing to travel, however, questions emerged regarding the risk of disease transmission in the air travel system, and specifically in the aircraft cabin. Although the risk of SARS-CoV-2 transmission among the flying public is perceived to be high, a data-driven approach is required to determine the actual range of risk.

It is important to differentiate between COVID-19 cases imported by air travel (i.e. an index passenger travels to a new location and transmission occurs on the ground); cases as a result of transmission during air travel (i.e. in the airplane cabin); and transmission in the air travel system which includes other locations beyond the airplane cabin where transmission might occur, e.g., airports. This paper quantifies the risk of SARS-CoV-2 transmission by estimating the risk in the air travel system from data collected during the pandemic and also corrects for known data limitations. Acknowledging that COVID-19 testing and reporting requirements vary by locality and can be difficult to connect to air travel, uncertainties are included in these risk calculations to more conservatively estimate risk. This paper is limited to publicly available literature which primarily considers infectious passengers and potential secondary transmissions in the air travel system; transmission involving airport personnel such as Transportation Security Administration (TSA) agents or crew are not addressed.

* Corresponding author. PO Box 3707, MC: 42-205, Seattle, WA, 98124, USA.

E-mail address: jenna.k.pang@boeing.com (J.K. Pang).

<https://doi.org/10.1016/j.tmaid.2021.102133>

Received 9 April 2021; Received in revised form 17 June 2021; Accepted 22 June 2021

Available online 26 June 2021

1477-8939/© 2021 Elsevier Ltd. All rights reserved.

2. Methods

2.1. Literature review for air travel transmission cases

A literature review was performed from May to September 2020 to identify index and secondary COVID-19 cases related to transmission in the air travel system for travel from January to September 2020. Index cases are those who tested positive for COVID-19 upon arrival at their destination. Thus, based on the incubation period of the disease, these passengers were identified as infected prior to entering the air travel system. Secondary cases are persons who traveled on a flight with an index passenger, tested positive for COVID-19 after the flight, and were identified through contact tracing to have most likely been infected via transmission from the index passenger. Publications were collected using English-language search terms linking COVID-19 and air travel from two primary paths: review of daily news articles and social media posts (referencing published research) or direct search of scientific publication repositories (arXiv.org, medRxiv, Clarivate, LitCovid, PubMed, and the United States Centers for Disease Control and Prevention (CDC)'s COVID-19 research database). Additional papers were identified by biomedical experts at International Air Transport Association (IATA) and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO). Only studies accepted by a journal for publication or by a preprint server were reviewed due to their expected higher quality of information on flights taken by an index passenger and subsequent contact tracing. Two additional studies performed by IATA and the CDC were added to the review due to these organizations' oversight and data collection capabilities, despite the limited visibility into the data collection methods and sources. Acknowledging that the variability of recommended behaviors and policies across airlines and governments during the pandemic likely leads to confounding issues in all papers cited in this study (i.e. mask use, seating) as well as a lack of similar study design, no results were disqualified in the interest of making a conservative estimate of risk.

The majority of publicly available studies focused on infectious passengers and related transmissions, therefore the study was limited to flights with passenger index cases and did not include transmission amongst air crews, ground crews, or airport staff. Six experts in risk, epidemiology, virology, human factors, microbiology, and civil engineering separate to the authors reviewed each study and independently extracted flight information (date, departure and arrival cities, and time of flight), number of index cases, and number of secondary cases as well as available data on passenger behavior. Conservatively, all probable secondary cases identified in the literature are included in risk calculations. Study duplications were recognized by comparing flight information and the study with more information about passenger contact tracing was kept in the review. Discussions were held amongst the reviewing team (experts and authors) to confirm validity of identified secondary cases being infected in the air travel system, most specifically the airplane cabin, by studying information about passenger behavior and positive test dates and comparing against information known in September 2020 about the index infectiousness period, symptom onset, and the COVID-19 incubation period. Group consensus on the number of index and secondary cases was required before proceeding on with the study. To verify reasonable interpretations of the review, conversations were held with IATA and the organization's Medical Advisor, Dr. David Powell (author of [29]), to ensure all publicly known flights with transmission were included in the review and to consider the organization's understanding of air travel system risk.

The majority of studies in the literature review focused on a single flight with known secondary cases. Other studies outlined multiple flights, but made qualitative statements on risk based only on the select handful of flights reviewed. News stories released by media and not included in this review indicated index cases aboard many more flights than covered in the published papers, but did not follow up on contact tracing results or identification of secondary cases. A nuanced

understanding of air travel system risk should therefore consider the full range of air travel experiences during the pandemic from a flight with multiple secondary cases and no mitigation techniques to a flight with no infectious passengers.

2.2. Calculation of estimated risk of transmission

To estimate the risk of air travel system transmission, a quantitative approach was taken that considers secondary cases and the overall air travel passenger population. A novel approach to transmission risk was developed which uses two correction factors for asymptomatic transmission and underreporting to address the confounding factors and study heterogeneity identified during the literature review and to more conservatively estimate risk. The number of infected persons in the transmission events identified in Section 2.1 was determined through either mandatory screening or self-reporting, and it is likely that this count of infected persons is much lower than the true number of persons who have been infected while in the air travel system. Therefore, a number of caveats must be considered for potential error in the risk calculation. The first is the number of people who are infected, but are asymptomatic. Per the Centers for Disease Control and Prevention (CDC), asymptomatic infections are nominally estimated to be 40% of the total infections and asymptomatic individuals are estimated to be 75% as infectious as a symptomatic individual [5]. This indicates a factor of 1.3x if assuming asymptomatic passengers are not fully counted as index or secondary cases in the data. The second issue is the number of unreported COVID-19 cases, both index and secondary, in relation to air travel which includes:

- Symptomatic passengers who seek medical attention for symptoms, but do not inform medical personnel of their travel;
- Symptomatic passengers who seek medical attention for symptoms, but medical personnel fail to report travel; and
- Symptomatic passengers who do not seek medical attention.

To account for underreported air travel cases, the number of unreported COVID-19 cases in the general global population is assumed to apply. Recent estimates indicate global under-reporting to be a 10-fold [6,7], 23-fold [8] and 54-fold [9] multiplier of the current reported cases.

With these caveats, the equation for estimated risk of transmission is as follows:

$$\text{estimated risk of transmission} = \frac{n_t}{n_p} \times f_a \times f_c \quad 1$$

where n_t is the number of secondary cases due to air travel transmission, n_p is the total passenger population, f_a is the factor to account for number of and infectiousness of asymptomatic cases, and f_c is the factor to account for number of unreported cases.

3. Results

3.1. COVID-19 transmission events in the air travel system

During the pandemic it has been estimated that, even with a significant decline in air travel, approximately 1.4 billion passengers traveled by air between January and September 2020 [10]. As of August 2020, there were at least 2866 index passengers documented to have passed through the air travel system (Table 1). Due to the widespread prevalence of the disease and presence of pre-symptomatic, asymptomatic, and mildly symptomatic cases in the population, it is known that there likely have been additional COVID-19 infectious passengers entering the travel system, beyond the identified index cases. Nonetheless, review of publicly available data reveals fewer than 50 documented potential secondary cases have been associated with air travel during the

Table 1
Flight, passenger and reference list for index persons and secondary cases due to transmission.

Flight Information		Affected Persons			Location of Diagnosis	Flight Duration	Mask Use ^a	Author
Date (MM/DD/YYYY)	Country and/or City Pair	Index	Secondary (due to Transmission)	Total Number of Passengers				
General IATA Data		1100	3	Unknown	Unknown	Unknown	U	IATA [33]
General CDC Data		1600	0	Unknown	Unknown	Unknown	U	Duncan [34]
1/22/2020	China-Toronto	1	0	350	Canada	15 h	U	Schwartz et al. [24]
1/24/2020	Singapore-Hangzhou	15	1	335	China	4 h 50 m	O	Chen et al. [11]
2/20/2020	Tokyo-Tel Aviv	2	0	11	Israel	16 h ^b	M	Freedman and Wilder-Smith [13]
2/24/2020	Bangui (CAR)-Yaounde (CMRN)-Paris	1	1	164	France	1 h 30 m + 6 h 45 m	U	Eldin et al. [25]
2/26/2020	Multiple -Greece	21	5	2224	Greece, other	2 h ^c	U	Pavli et al. [14]
3/2/2020	London-Hanoi	1	15	201	Vietnam	10 h	U	Khanh et al. [17]
3/9/2020	Tel Aviv-Frankfurt	7	2	102	Germany	4 h 40 m	O	Hoehl et al. [26]
3/10/2020	Boston-Hong Kong	2	2	274	Hong Kong SAR	15 h	U	Choi et al. [27]
3/19/2020	Sydney-Perth	11	11	241	Australia	5 h	O	Speake et al. [28]
3/30/2020	New York City-Taipei	9	0	340	Taiwan	15 h 50 m	M	Freedman and Wilder-Smith
3/31/2020	Milan-South Korea	6	1	310	S. Korea	11 h	M	Bae et al. [12]
4/3/2020	Milan-South Korea	3	1	205	S. Korea	11 h	M	Bae et al.
6/20/2020	Dubai-Hong Kong	85	2	864	Hong Kong SAR	8 h	M	Freedman and Wilder-Smith; IATA [29]
Total		2866	44					

^a Mask use categories: U = unavailable (data not reported); O = optional (mask use was not described as mandatory, mask use was not listed as mitigation, use described as “rare”); M = mandatory mask use.

^b Flight duration was not specified by original study authors; used average flight time reported by Google Flights between city pair.

^c Multiple flights were included in this study and therefore, the reported flight duration is for the flights with reported transmission to passengers (Israel – Greece). Other flights of varying duration had reports of with index passengers.

pandemic. Mask use on reviewed flights ranged from use unknown to mandatory N95 use; of the 13 flight-specific entries, 5 mandated mask use, 3 had optional mask use, and 5 did not have mask data available. Of the reviewed flights, 7 had COVID-19 testing of the entire passenger population within the first days of arrival at a minimum; the other flights did not perform systemic testing and used contact tracing to identify cases.

Table 1 documents the index and secondary cases for passengers who have flown during the pandemic. IATA and CDC data are included for thoroughness with the acknowledgement that limited details are known about the data methods and sources and that case counts may be duplicates of other reported cases. For the purpose of this study, transmission from the index passenger was conservatively assumed to have occurred inside the air travel system in each of these documented cases, although transmission could have occurred elsewhere, such as during transport to the airport.

3.2. Epidemiological study of SARS-CoV-2 in flight

Some studies were able to more clearly trace index and secondary

case relationships to a flight. An epidemiological study of the January 24, 2020 flight from Singapore to Hangzhou, China with a number of confirmed COVID-19 cases on board (Fig. 1) was completed [11]. This flight, which lasted approximately 5.5 hours, was loaded at 89% capacity. Upon arrival at the destination, all passengers and crew were quarantined and tested several days after arrival, one week after arrival, and if displaying symptoms. The study determined that of the 16 passengers who ultimately tested positive for COVID-19, 15 of the passengers were index cases on the flight due to the timing of symptom onset; if they had been infected on the flight, they would not have had symptoms immediately after the flight. The index cases had membership in one of three tour groups with other passengers who also tested positive for COVID-19 and originated in Wuhan. Only one passenger was identified to be a potential secondary case of SARS-CoV-2 in flight due to a different city of origin (Hangzhou), membership in a different tour group with no recorded cases of COVID-19, and reported activity of temporarily moving to an unassigned seat surrounded by infectious and symptomatic passengers during the flight as indicated in Fig. 1. All 16 passengers wore masks during air travel, but removed their masks during meal time and to drink water; the mask of the secondary case was

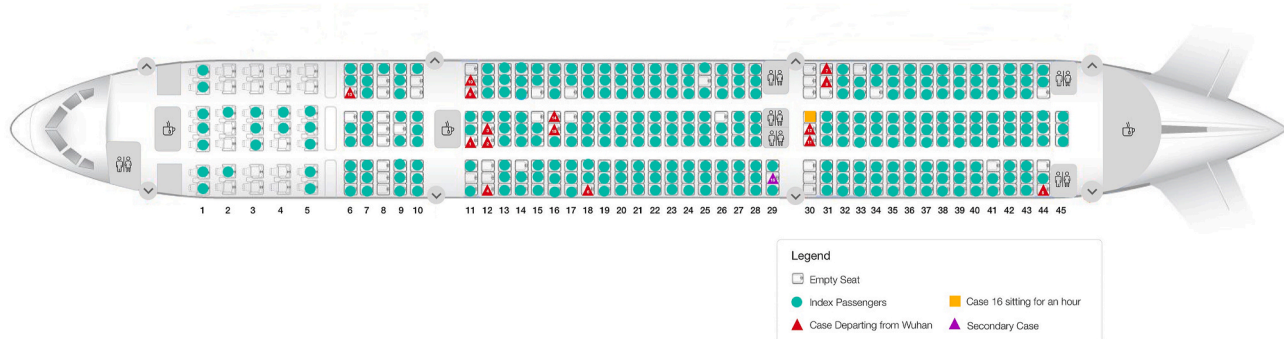


Fig. 1. Seat map of flight with 15 index passengers and one possible secondary case.

not worn tightly and did not cover their nose when sitting in the unassigned seat.

3.3. Estimated risk of transmission

In addition to the unknown flight dates for the IATA and CDC data, there are 12 flights that occurred March 2020 or earlier, while flight traffic was still high, in areas like Europe and the United States. To take a conservative position on risk, transmission risk was calculated for three time periods of interest: (1) January–June 2020 during which the transmission events listed in Table 1 occurred, (2) the month of March 2020 when the global spread of COVID-19 was occurring, and (3) April–September 2020 to account for the sharp drop in worldwide air travel and increased use of COVID-19 testing. For a slightly more conservative risk calculation, the 3 secondary cases recorded by IATA were included in the multi-month risk calculations (January–June 2020, April–September 2020) based on the assumption that March was a well-documented month, so it is unlikely that these cases are duplicates of the transmission events in that month. Passenger counts were derived from International Civil Aviation Organization (ICAO) monthly reporting of actual passenger totals [10]. Table 2 lists the estimated risk of SARS-CoV-2 transmission in the air travel system for the global public as calculated with Equation (1).

For 44 secondary cases from January–June 2020 with a 1.3-fold factor for asymptomatic persons (f_a) and a 10-fold factor for underreporting (f_c) against a population of 968 million travelers, the risk of being infected with SARS-CoV-2 in an airplane cabin is estimated to be 5.927×10^{-7} or 1:1.7 million. A 54-fold multiplier of reported cases gives a risk of 3.201×10^{-6} or a 1:0.3 million (1:312,419) chance of being infected with COVID-19 in the airplane cabin.

Due to increased availability and reliability of COVID-19 testing and localized variability in reporting since the start of the pandemic, statistics for asymptomatic persons, infectiousness, and underreporting carry a degree of uncertainty which affects the overall risk calculation. The CDC indicates that asymptomatic cases could range from 10 to 70% of the infected population and that asymptomatic infectiousness ranges from 0.25 to 1.00 [5]. The Chow et al. study indicates a 95% credible interval for an estimated 10-fold underreporting factor ranges from 2.2 to 50 [7]. For this paper’s treatment of risk, uncertainty is established by first identifying the uncertainty in factors f_a and f_c in Equation (1), next fitting triangular distributions to each statistic with the peak at the baseline values stated above, then running 1 million simulations with a draw from each distribution to calculate risk, and finally selecting the

Table 2
Estimated risk of SARS-CoV-2 transmission in the air travel system for the global public in 2020.

Dates	n_t	n_p (million)	f_a	f_c	Risk	
					Numerical	1 in X
January–June 2020	44	965	1.3	10	5.927×10^{-7}	1,687,063
				23	1.363×10^{-6}	733,506
				54	3.201×10^{-6}	312,419
March 2020	31	171.3	1.3	10	2.353×10^{-6}	425,062
				23	5.411×10^{-6}	184,810
				54	1.270×10^{-5}	78,715
April–September 2020	6	552	1.3	10	1.413×10^{-7}	7,076,923
				23	3.250×10^{-7}	3,076,923
				54	7.630×10^{-7}	1,310,541

2.5% and 97.5% risk estimate from the 1 million simulations which set the bounds of the uncertainty interval. Using the above literature estimates of uncertainty in the parameters of f_a and f_c , uncertainty in the transmission risk is estimated to range from 1 case for every 0.7 million (712,000) travelers to 1 case for every 8 million travelers.

At the onset of the pandemic in March, the estimated risk of transmission was 2.353×10^{-6} or 1:425,062 ($f_c = 10$). Estimated risk of being infected with COVID-19 could have been as high as 1:78,715 (1.27×10^{-5} , $f_c = 54$). In comparison, estimated risk during the pandemic (April–September 2020) ranges from 1:1.3 million ($f_c = 54$) to 1:7.1 million ($f_c = 10$) with reduced passenger traffic and few documented secondary cases.

4. Discussion

Fewer than 50 passenger-related secondary cases were recorded in the air travel system during the period of January–September 2020. There is documented evidence of flights with multiple infectious passengers but few or no secondary cases recorded [12–14]. Moreover, the majority of the documented secondary cases occurred on flights in March 2020 or earlier, when current common practices like wearing face masks, increasing spacing between passengers in the airport and when boarding/deplaning, systemic testing prior to and after flights, lockdown measures in countries of departure and arrival, and increased sanitization varied by region [15]. A notable finding of the Chen et al. [11] study discussed above is that only one possible secondary case was identified despite the large fraction of passengers on this flight, next to, in front of and behind index passengers. While physical distancing recommendations of many health organizations worldwide recommend 6 feet of separation to lower transmission risk [16], the results of this study indicate the actual risk of transmission in an aircraft cabin could be very low despite the relatively close proximity of passengers. In contrast, 15 secondary cases were associated with the London-Hanoi flight on March 2, 2020. However, all of these 15 passengers had either hotel, cruise ship, secondary transportation, travel to a second country, or known contact with other infectious persons not from the flight, or combinations thereof, after the flight from London to Hanoi and prior to testing [17]. In addition, based on the arrival date of the flight (March 2) and the earliest date of the subsequent reverse transcriptase polymerase chain reaction (RT-PCR) tests (March 6), it is possible that the potential secondary cases were infected post-flight since a positive test via PCR can occur on average 2–5 days after infection [18]. Finally, the testing of the London to Hanoi passengers did not include genomic analysis of the virus and therefore it was not possible to demonstrate that all of the secondary cases map to the same index case by sequence similarity. For these reasons, the causal connection between the London to Hanoi flight and the eventual positive test results for the 15 cases is in question. These findings warrant a detailed analysis of the aircraft cabin environment that could explain how such results are possible [19].

The ICAO traveler population numbers, used in risk calculations presented herein, include global passengers from regions such as Africa with less immediate outbreaks of COVID-19. Their inclusion could lower the ratio of infectious passengers to all passengers. Risk is also lowered by decreased worldwide air travel starting in March 2020 and limitation of air travelers to a small self-selecting subset of the global population, therefore a 10-fold change is assumed sufficient for a baseline estimated risk of transmission during air travel. Recognizing that studies could be ongoing to identify transmission events in the air travel system from summer 2020 on, the estimated transmission risk calculated for January–June 2020, 5.927×10^{-7} or 1:1.7 million ($f_c = 10$), should be considered the baseline estimated risk of transmission. With uncertainty, this risk ranges from 1 case for every 0.7 million (712,000) travelers to one case for every 8 million travelers.

While the risk of transmission in March 2020 in the general population was higher than current estimates, SARS-CoV-2 transmission

during air travel in March was still a low probability event. It should be noted that these calculations are based on limited testing of 2020 travelers and limited publicly available data, and are subject to the forces of a shifting global pandemic. The evaluated studies used different study methodologies with approaches ranging from contact tracing after a self-reported positive test to enforced quarantine as well as differing levels of reporting on mitigation methods. Studies were subject to varying local and governmental policies, test availability, and data availability (i.e. patient data, genomic sequencing). The risk approach does not serve to evaluate the efficacy of these study methodologies or mitigation methods. The risk approach is subject to reporting bias related to the link of air travel with disease transmission. Passengers who notice they are ill after a flight often anecdotally blame sickness on air travel. They therefore may be biased to report an event of COVID-19 transmission on a flight through the self-reporting and/or phone surveys used in place of quarantine procedures for some of the evaluated flights instead of transmission due to other behaviors. In fact, these phone surveys may also introduce ascertainment bias as researchers have identified flights to study by searching for flight-related COVID-19 cases. In addition, researchers searching for flight-related transmission may have the same personal anecdotal beliefs as passengers and could be biased towards higher case counts by assuming transmission over importation or through focus on international instead of domestic flights. It is likely that these sources of bias have resulted in greater numbers of reported COVID-19 cases related to air travel.

While the specific numbers will change as more flights are made, tests performed, and papers published, the reports for dates covered by this study indicate a low risk of transmission during air travel. Research on disease transmission in flight from other viruses such as from SARS-CoV-1 [20], Influenza [21], and Tuberculosis [22] has shown that the risk of known communicable diseases being transmitted aboard aircraft is low [23]. The inclusion of the two factors for asymptomatic transmission and underreporting are a novel approach to evaluating air travel system risk for COVID-19 and lessen the impact of confounding factors and heterogeneous pandemic studies. This is a more nuanced approach to assessing COVID-19 air travel system transmission risk than assuming a high degree of risk from select worst case scenarios; the probability of an infectious person aboard an airplane is not equal to the probability of a SARS-CoV-2 transmission to another person aboard that aircraft.

5. Conclusion

Data available during 2020 has shown that the risk of known communicable diseases being transmitted aboard aircraft is low [23]. This conclusion is consistent with studies on disease transmission in flight from other viruses such as from SARS-CoV-1 [20], Influenza [21], and Tuberculosis [22]. Similarly, the risk of SARS-CoV-2 transmission during air travel, calculated on data presented in Table 2 is on average approximately 1:1.7 million, however it is acknowledged that assumptions exist around case detection rate and lack of mass screenings to confirm. Given the global spread of COVID-19, it is clear that infectious individuals, including asymptomatic individuals, have been traveling by air. However, there has not been the large number of secondary cases that might be expected. Analysis of the limited reporting on infections traced to the air travel environment during the current COVID-19 pandemic supports the conclusion that even with infectious persons onboard, the overall risk of contracting COVID-19 from such an index passenger is low [11–14,24–29]. In addition, the improvement in safety provided by wearing masks is well established [30–32] and the results presented herein, particularly the reduction in estimated risk observed from April through September 2020 when masks were more widely used in the air travel system than prior to April, supports the recommendation that masks be worn properly at all times when in the air travel system.

It is thought that the environmental control systems on the aircraft, which are more effective than those in common commercial spaces that the public may experience, contribute to the low probability of infection

in the air travel system. Specifically, the high airflow, high-efficiency particulate air (HEPA) filtration, and seat-height/passenger-positioning (passengers do not face one another for the majority of the flight) are thought to minimize air flow between rows and protect passengers from infectious particle transfer. Studies of the engineering controls on aircraft are currently being prepared for publication by the authors.

Funding

This work was supported by The Boeing Company.

CRediT authorship contribution statement

Jenna K. Pang: Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Stephen P. Jones:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Lindsay L. Waite:** Methodology, Formal analysis. **Nels A. Olson:** Conceptualization, Investigation, Writing – review & editing. **Jason W. Armstrong:** Investigation, Writing – review & editing. **Robert J. Atmur:** Conceptualization. **Joshua J. Cummins:** Conceptualization, Project administration, Writing – review & editing.

Declaration of competing interest

All authors are employees of The Boeing Company.

Acknowledgments

The authors wish to thank Dr. David Powell, Medical Advisor for IATA and Dr. Sankaran Mahadevan at Vanderbilt University for thoughtful discussions on risk.

References

- [1] World Health Organization. Archived: WHO timeline - COVID-19. <https://www.who.int/news/item/27-04-2020-who-timeline-covid-19>. [Accessed 21 September 2020].
- [2] World Health Organization. WHO field visit to wuhan. China 20-21 January 2020. <https://www.who.int/china/news/detail/22-01-2020-field-visit-wuhan-china-jan-2020>. [Accessed 21 September 2020].
- [3] World Health Organization. Novel coronavirus (2019-nCoV): strategic preparedness and response plan; draft as of february 3, 2020. World Health Organization, <https://www.who.int/docs/default-source/coronaviruse/srp-04022020.pdf>. [Accessed 21 September 2020].
- [4] Ellwood M. Coronavirus air travel: these numbers show the massive impact of the pandemic. Conde Nast Traveler. April 13, 2020, www.cntraveler.com/story/coronavirus-air-travel-these-numbers-show-the-massive-impact-of-the-pandemic. [Accessed 21 September 2020].
- [5] United States Centers for Disease Control and Prevention. COVID-19 pandemic planning scenarios. <https://www.cdc.gov/coronavirus/2019-ncov/hcp/planning-scenarios.html>. [Accessed 8 October 2020].
- [6] Rahmandad H, Lim TY, Sterman J. Estimating COVID-19 under-reporting across 86 nations: implications for projections and control. medRxiv. Preprint, version 2. Preprint posted online August 3, 2020. <https://doi.org/10.1101/2020.06.24.20139451>.
- [7] Chow CC, Chang JC, Gerkin RC, Vattikuti S. Global predication of unreported SARS-CoV2 infection from observed COVID-19 cases. medRxiv. Preprint posted online May 2020;5. <https://doi.org/10.1101/2020.04.29.20083485>.
- [8] Hortaçsu A, Liu J, Schwieg T. Estimating the fraction of unreported infections in epidemics with a known epicenter: An application to COVID-19. J Econom 2021; 220:106–29. <https://doi.org/10.1016/j.jeconom.2020.07.047>.
- [9] Lau H, Khosrawipour T, Kobach P, Ichii H, Bania J, Khosrawipour V. Evaluating the massive underreporting and underesting of COVID-19 cases in multiple global epicenters. Pulmonology 2021;27:110–5. <https://doi.org/10.1016/j.pulmoe.2020.05.015>.
- [10] Effects of novel coronavirus (COVID-19) on civil aviation: economic impact analysis. Air Transport Bureau, International Civil Aviation Organization; 2020. https://www.icao.int/sustainability/Documents/COVID-19/ICAO_Coronavirus_Econ_Impact.pdf. [Accessed 13 October 2020].
- [11] Chen J, He H, Cheng W, Liu Y, Sun Z, Chai C, et al. Potential transmission of SARS-CoV-2 on a flight from Singapore to Hangzhou, China: an epidemiological investigation. Trav Med Infect Dis 2020;36:101816. <https://doi.org/10.1016/j.tmaid.2020.101816>.

- [12] Bae SH, Shin H, Koo H-Y, Lee SW, Yang JM, Yon DK. Asymptomatic transmission of SARS-CoV-2 on evacuation flight. *Emerg Infect Dis* 2020;26:2705–8. <https://doi.org/10.3201/eid2611.203353>.
- [13] Freedman DO, Wilder-Smith A. In-flight Transmission of SARS-CoV-2: a review of the attack rates and available data on the efficacy of face masks. *J Trav Med* 2020; 27:taaa178. <https://doi.org/10.1093/jtm/taaa178>.
- [14] Pavli A, Smeti P, Hadjianastasiou S, Theodoridou K, Spilioti A, Papadima K, et al. In-flight transmission of COVID-19 on flights to Greece: an epidemiological analysis. *Trav Med Infect Dis* 2020;38:101882. <https://doi.org/10.1016/j.tmaid.2020.101882>.
- [15] Elachola H, Ebrahim SH, Gozzer E. COVID-19: facemask use prevalence in international airports in Asia, Europe and the Americas, March 2020. *Trav Med Infect Dis* 2020;35:101637. <https://doi.org/10.1016/j.tmaid.2020.101637>.
- [16] United States Centers for Disease Control and Prevention. Social distancing, keep a safe distance to slow the spread. <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/social-distancing.html>. [Accessed 21 September 2020].
- [17] Khanh NC, Thai PQ, Quach HL, Thi NAH, Dinh PC, Duong TN, et al. Transmission of severe acute respiratory syndrome coronavirus 2 during long flight. *Emerg Infect Dis* 2020;26:2617–24. <https://doi.org/10.3201/eid2611.203299>.
- [18] World Health Organization. Advice on use of masks in the context of COVID-19: interim guidance, 5 June 2020. World Health Organization; 2020. https://apps.who.int/iris/bitstream/handle/10665/332293/WHO-2019-nCov-IPC_Masks-2020.4-eng.pdf. [Accessed 13 October 2020].
- [19] Silcott D, Kinahan S, Santarpia J, Silcott B, Silcott R, Silcott P, et al. TRANSCOM/AMC commercial aircraft cabin aerosol dispersion tests. United States transport command. US Dept of Defense; 2020. <https://www.ustranscom.mil/cmd/doc/s/TRANSCOM%20Report%20Final.pdf>. [Accessed 16 October 2020].
- [20] Olsen SJ, Chang HL, Cheung TYY, Tang AFY, Fisk TL, Ooi SPL, et al. Transmission of the severe acute respiratory syndrome on aircraft. *N Engl J Med* 2003;349: 2416–22. <https://doi.org/10.1056/NEJMoa031349>.
- [21] Leitmeyer K, Adlhoch C. Influenza transmission on aircraft, A systematic literature review. *Epidemiology* 2016;27:743–51. <https://doi.org/10.1097/EDE.0000000000000438>.
- [22] World Health Organization. Tuberculosis on aircraft. In: World health organization. Tuberculosis and air travel: guidelines for prevention and control. third ed. World Health Organization; 2008. chap 2. Available from: <https://www.ncbi.nlm.nih.gov/books/NBK143710/>.
- [23] Mangili A, Gendreau MA. Transmission of infectious diseases during commercial air travel. *Lancet* 2005;365:989–96. [https://doi.org/10.1016/S0140-6736\(05\)71089-8](https://doi.org/10.1016/S0140-6736(05)71089-8).
- [24] Schwartz KL, Murti M, Finkelstein M, Leis JA, Fitzgerald-Husek A, Bourns L, et al. Lack of COVID-19 transmission on an international flight. *CMAJ (Can Med Assoc J)* 2020;192:E410. <https://doi.org/10.1503/cmaj.75015>.
- [25] Eldin C, Lagier JC, Mailhe M, Gautret P. Probable aircraft transmission of Covid-19 in-flight from the Central African Republic to France. *Trav Med Infect Dis* 2020;35: 101643. <https://doi.org/10.1016/j.tmaid.2020.101643>.
- [26] Hoehl S, Karaca O, Kohmer N, Westhaus S, Graf J, Goetsch U, et al. Assessment of SARS-CoV-2 transmission on an international flight and among a tourist group. *JAMA Netw Open* 2020;3:e2018044. <https://doi.org/10.1001/jamanetworkopen.2020.18044>.
- [27] Choi EM, Chu DKW, Cheng PKC, Tsang DNC, Peiris M, Bausch DG, et al. In-flight transmission of SARS-CoV-2. *Emerg Infect Dis* 2020;26:2713–6. <https://doi.org/10.3201/eid2611.203254>.
- [28] Speake H, Phillips A, Chong T, Sikazwe C, Levy A, Lang J, et al. Flight-associated transmission of severe acute respiratory syndrome coronavirus 2 corroborated by whole-genome sequencing. *Emerg Infect Dis* 2020;26:2872–80. <https://doi.org/10.3201/eid2612.203910>.
- [29] Powell D. Is the cabin environment safe? International Air Transport Association 2020:4–6. <https://www.iata.org/contentassets/fl163430bba94512a583eb6d6b24aa56/pha-webinar.pdf>. [Accessed 9 October 2020].
- [30] Leung NHL, Chu DKW, Shiu EYC, Chan K-H, McDevitt JJ, Hau BJP, et al. Respiratory virus shedding in exhaled breath and efficacy of face masks. *Nat Med* 2020;26:676–80. <https://doi.org/10.1038/s41591-020-0843-2>.
- [31] Loeb M, Dafoe N, Mahony J, John M, Sarabia A, Glavin V, et al. Surgical mask vs N95 respirator for preventing influenza among health care workers, A randomized trial. *J Am Med Assoc* 2009;302:1865–71. <https://doi.org/10.1001/jama.2009.1466>.
- [32] Bahl P, Bhattacharjee S, de Silva C, Chughtai AA, Doolan C, MacIntyre CR. Face coverings and mask to minimise droplet dispersion and aerosolisation: a video case study. *Thorax* 2020;75:1024–5. <https://doi.org/10.1136/thoraxjnl-2020-215748>.
- [33] International Air Transport Association. Restarting aviation following COVID-19. International Air Transport Association 2020:1–2. www.iata.org/contentassets/s/fl163430bba94512a583eb6d6b24aa56/covid-medical-evidence-for-strategies-200504.pdf. [Accessed 8 October 2020].
- [34] Duncan I. Nearly 11,000 people have been exposed to the coronavirus on flights, the CDC says. The Washington Post. September 19, 2020. www.washingtonpost.com/local/trafficandcommuting/nearly-11000-people-have-been-exposed-to-the-coronavirus-on-flights-the-cdc-says/2020/09/19/d609adbc-ed27-11ea-99a1-71343d03bc29_story.html. [Accessed 21 September 2020].