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Rijksinstituut voor Volksgezondheid en Milieu
Ministerie van Volksgezondheid, Welzijn en Sport

NLR-CR-2020-288 | October 2020

CORSICA literature report

Key findings from literature review on the SARS-CoV-2 transmission in aircraft cabins

CUSTOMER: Ministry of Infrastructure and Water Management

NLR – Royal Netherlands Aerospace Centre
RIVM – National Institute for Public Health and the Environment

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EXECUTIVE SUMMARY

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The coronavirus, COVID-19, has large consequences for aviation. Measures to combat COVID-19 have brought international aviation almost to a complete standstill in March 2020. RIVM advised on the safety on board of aircraft in relation to SARS-CoV-2 and the associated safety protocols put in place by Dutch airlines, based on guidelines by EASA and ICAO. RIVM deems it plausible that the ventilation system on board of aircraft, with a high air exchange rate and vertical air flows, limits possible transmission of SARS-CoV-2 on board of aircraft. Although the number of flights, following a short recovery during the summer, is still limited and little cases of SARS-CoV-2 contamination on board of aircraft are known at the moment, there are concerns about the contamination risk on board. Expanding the knowledge about the relevant factors and the effectiveness of currently implemented measures, can contribute to decision and policy making by travelers, airlines and authorities.

Description of work

Royal Netherlands Aerospace Centre (NLR) and the National Institute for Public Health and the Environment (RIVM) have been tasked by the Ministry of

Infrastructure and Water Management to conduct fact-based and objective research, consisting of simulations and measurements, on the SARS-CoV-2 contamination risk on board of aircraft. NLR primarily addresses aviation aspects and project coordination and RIVM is responsible for virology, exposure and health related aspects.

This report contains the results of the literature research and serves as input for the subsequent simulations and measurements. The final report will be published mid-December 2020.

Results and conclusions

The literature research has identified the factors relevant for the contamination of SARS-CoV-2 on board of aircraft, distinguishing between cabin conditions, the contamination source, transmission through the cabin and the exposure of a recipient. Additionally, literature on documented cases of SARS-CoV-2 on board of aircraft and currently applied mitigation measures has been reviewed.

Following the most recent RIVM research, a range of <1 – 2000 µm will be assumed for particle size. This span both larger as well as smaller droplets (so-called aerosols). It is assumed that all passengers and crew in the cabin wear non—medical face masks. Based on available literature, an inhalation filtering efficiency of 30% and an exhalation filtering efficiency of 60% are currently assumed.

Three relevant routes for virus transmission have been investigated: transmission by means of larger droplets (e.g. following sneezing or coughing), transmission by means of aerosols (exhaled by breathing) and contact transmission. The relative importance of these routes is subject of discussion in literature and is difficult to determine, although literature seems to note little cases of contact transmission. The simulations and measurements will therefore address the first two routes. For transmission by means of larger droplets, the use of mouth masks, good sneezing and coughing hygiene and gravity effects seem most relevant; for transmission by means of aerosols, air flows play a large role. These air flows are not only influenced by the ventilation system, but also by the physical presence and heat of passengers in the cabin.

In the next phase of this research, simulations and measurements will be used to complement theoretical knowledge with practical results thereby determine the contamination risk of SARS-CoV-2 on board of aircraft. The optimal combination of simulations and measurements will too be determined in that phase. To enable validation of the findings, the simulation work will start with a base scenario of the most common circumstances (cruise flight), for which data from literature is available. Later, additional scenarios are to be added. Measurements provide the most realistic representation of reality. Depending on the strategy, measuring cabin conditions and measuring actual transmission can both be considered. To ensure the highest level of realism, actual aircraft types rather than generic models will be considered. Based on the commonality at Schiphol, the Boeing 737 and Airbus A320 are identified as representative single-aisle aircraft. For the larger twin-aisle aircraft, the Boeing 777 and 787 are evident choices.

Applicability

This report contains the results of the literature research and serves as input for the subsequent simulations and measurements in the CORSICA project. The research is limited to SARS-CoV-2 transmission on board of large aircraft used for commercial passenger transport.

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Samenvatting

Probleemstelling

Het coronavirus, COVID-19, heeft grote gevolgen voor de luchtvaart. De genomen maatregelen in de strijd tegen COVID-19 hebben de internationale luchtvaart in maart 2020 vrijwel volledig tot stilstand gebracht. Het RIVM heeft begin juni advies gegeven over de veiligheid aan boord van vliegtuigen in verband met COVID-19. Ook heeft het RIVM advies gegeven op de protocollen van de Nederlandse luchtvaartmaatschappijen. De basis voor de protocollen ligt in de EASA- en ICAO-richtlijnen. Het RIVM stelt in dit advies dat het plausibel is dat de ventilatiesystemen aan boord van vliegtuigen met hoge luchtverversing en verticale luchtstromen een beperking geeft op eventuele overdracht van SARS-CoV-2 aan boord. Hoewel er na een korte opleving gedurende de zomerperiode nog steeds weinig wordt gevlogen en er weinig gevallen van SARS-CoV-2 aan boord van vliegtuigen bekend zijn, zijn er tegelijkertijd zorgen over het risico op besmetting aan boord. Door de kennis over de relevante factoren en de effectiviteit van de genomen maatregelen aan te vullen, kan worden bijdragen aan de besluit- en beleidsvorming door reizigers, luchtvaartmaatschappijen en autoriteiten.

Beschrijving van de werkzaamheden

Het Koninklijk Nederlands Lucht- en Ruimtevaartcentrum (NLR) en het Rijksinstituut voor Volksgezondheid en Milieu (RIVM) hebben van het Ministerie van Infrastructuur en Waterstaat de opdracht gekregen om feitelijk en objectief onderzoek bestaande uit literatuuronderzoek, simulaties en metingen te doen naar de besmettingsrisico's voor COVID-19 aan boord van vliegtuigen. Hierbij richt NLR zich primair op de luchtvaartaspecten en projectcoördinatie en het RIVM op virologie en blootstellings- en gezondheidsaspecten.

Dit rapport bevat de resultaten van het literatuuronderzoek en dient om input te geven aan de hierop volgende simulaties en metingen. Het eindrapport zal medio december 2020 worden opgeleverd.

Resultaten en conclusies

Het literatuuronderzoek heeft de factoren in beeld gebracht die relevant zijn voor de verspreiding van SARS-CoV-2 aan boord van vliegtuigen, onderverdeeld in cabine-condities, de bron van besmetting, verspreiding door de cabine en blootstelling van een ontvanger. Tevens is gekeken naar reeds bekende besmettingsgevallen uit de literatuur en naar literatuur met betrekking tot reeds genomen mitigatiemaatregelen.

Voor de grootte van de virusdeeltjes wordt conform het meest recente RIVM-onderzoek een bandbreedte van <1 – 2000 µm aangehouden, deze omvatten zowel grotere druppels als kleinere druppels (zogeheten aerosolen). Aangenomen wordt dat alle passagiers en bemanningsleden in de cabine niet-medische mondmaskers dragen. Op basis van beschikbare literatuur wordt vooralsnog een efficiëntie van 30% bij inademen en 60% bij uitademen voor deze maskers aangenomen.

Er zijn drie relevante routes voor virusverspreiding onderzocht: verspreiding via grotere druppels (o.a. door niezen of hoesten), verspreiding via aerosolen (in de adem) en besmetting via oppervlakten. Het relatieve belang van deze routes voor de virusverspreiding is onderwerp van discussie in de literatuur en is lastig te bepalen, al lijkt besmetting via oppervlakten volgens de literatuur weinig voor te komen. De simulaties en metingen zullen zich dan ook richten op de eerste twee routes. Bij verspreiding via grotere druppels lijken gebruik van mondkapjes, goede nies- en hoesthygiëne en zwaartekrachteffecten het meest relevant, bij aerosolen-verspreiding spelen de luchtstromen een

grote rol. Deze luchtstromen worden niet alleen door het ventilatiesysteem beïnvloed, maar ook door de fysieke aanwezigheid en warmte van de passagiers in de cabine.

In de volgende fase van dit onderzoek worden simulaties en metingen gebruikt om de theoretische kennis aan te vullen met praktische resultaten en daarmee het besmettingsrisico van SARS-CoV-2 in vliegtuigen te bepalen. De optimale combinatie van simulaties en metingen wordt in dezelfde fase bepaald. Om validatie van de bevindingen mogelijk te maken wordt gestart met een basis-simulatiescenario onder de meest voorkomende omstandigheden (de kruisvlucht). Hiervoor is ook data uit de literatuur beschikbaar. Later worden andere scenario's toegevoegd. Metingen leveren de meest realistische benadering van de werkelijkheid. Afhankelijk van de gekozen aanpak kan zowel gekeken worden naar het meten van cabinecondities als naar daadwerkelijke verspreiding. Voor een zo hoog mogelijk realiteitsgehalte wordt uitgegaan van echte vliegtuigtypes in plaats van generieke modellen. Op basis van gangbaarheid op Schiphol zijn de Boeing 737 en Airbus A320 geïdentificeerd als representatief *single-aisle* vliegtuig. Voor de grotere *twin-aisle* toestellen zijn dat de Boeing 777 en 787.

Toepasbaarheid

Dit rapport bevat de resultaten van het literatuuronderzoek en dient om input te geven aan de hierop volgende simulaties en metingen van project CORSICA. Het onderzoek beperkt zich tot SARS-CoV-2 besmetting aan boord van grote vliegtuigen die worden ingezet voor commercieel passagiersvervoer.

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Acronyms and abbreviations

Acronym or term	Description
APU	Auxiliary Power Unit, on-board generator powering secondary aircraft systems during flight or the ECS on the ground when no PCA is available
CORSICA	**Co**ntamination **r**isk of **S**ARS-CoV-2 **i**n aircraft **ca**bins
COVID-19	Coronavirus disease 2019, infectious disease caused by the SARS-CoV-2 virus
DES	Detached eddy simulation
DNW	German-Dutch Wind Tunnels
EASA	European Aviation Safety Agency
ECS	Environmental Control System
gasper	Passenger-controlled air inlets often mounted overhead
HEPA	High Efficiency Particulate Air filter
IATA	International Airline Trade Association
ICAO	International Civil Aviation Organisation
IenW	Ministry of Infrastructure and Water Management
LES	Large eddy simulation
MPPS	Most Penetrating Particle Size
NLR	Royal Netherlands Aerospace Centre
packs	pneumatic air cycle kits
PCA	Pre-Conditioned Air (unit), mobile generator providing pre-heated air whilst the aircraft is on the ground
RANS	Reynolds-averaged Navier-Stokes
RIVM	Dutch National Institute for Public Health and the Environment
SARS-CoV-2	Severe Acute Respiratory Syndrome – Corona Virus 2, the virus that can cause the disease COVID-19
URANS	Unsteady Reynolds-averaged Navier-Stokes

1 Introduction

1.1 Context

The coronavirus pandemic is an ongoing global epidemic of coronavirus disease 2019 (COVID-19). The disease was first identified in December 2019 in Wuhan, China. The outbreak was declared a Public Health Emergency of International Concern in January 2020, and a pandemic in March 2020. As of 11 October 2020, more than 37.2 million cases have been confirmed as well as more than 1.07 million deaths attributed to COVID-19 and a loss in global GDP of 2-3%.

COVID-19 is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The disease spreads most often when infected people are physically close through the air. This occurs primarily via small droplets and sometimes in aerosols and may be transmitted via contaminated surfaces.

Once the medical severity of the pandemic became clear, most countries started imposing drastic measures to protect public health. These measures included unprecedented travel limitations to contain the virus. These restrictions almost completely halted air travel by the end of March 2020: less: less than 1% of last year's airport passenger traffic remained, as shown in Figure 1 (ACI Europe, 2020).

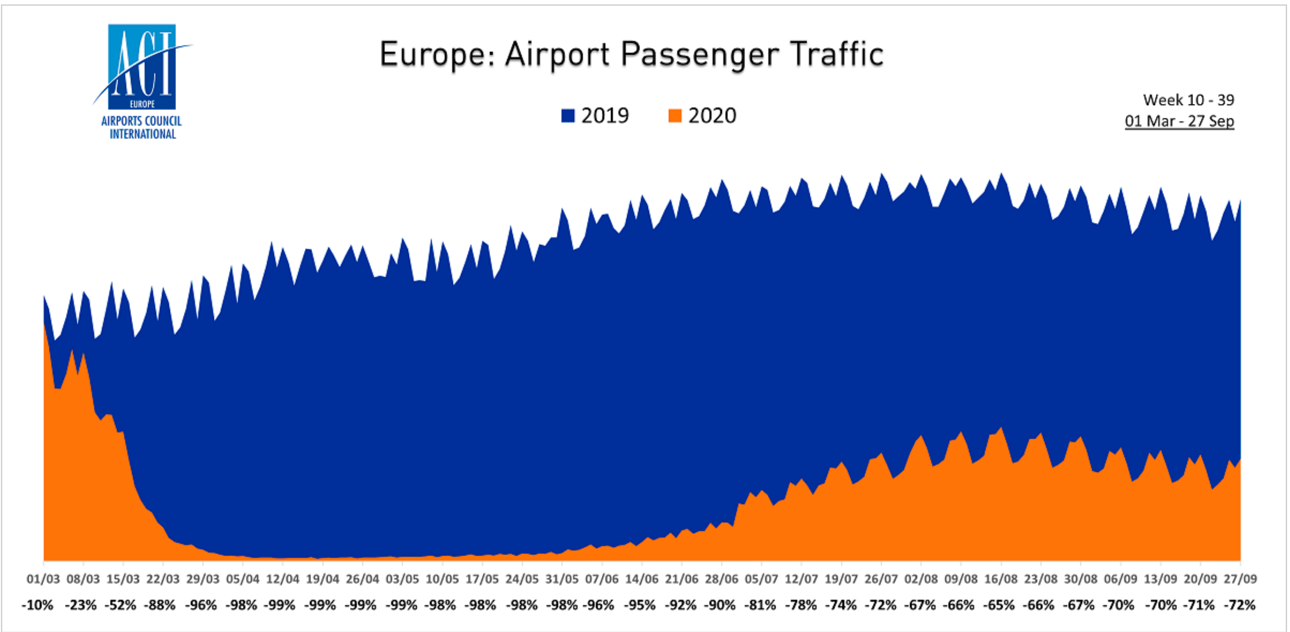

Figure 1: Airport passenger traffic March-September 2019 vs 2020 (ACI Europe, 2020)

Since June 2020, European air travel has slowly recovered to about 30% of 2019 levels, however as the pandemic is far from under control it is unclear when and how air travel will fully recover. As of now no large outbreaks of COVID-19 have been linked to SARS-CoV-2 transmission in aircraft, but studies identified viral transmission on a small number of flights (see Section 2.1 for an overview). Viral transmission of SARS-CoV-2 on board of aircraft is thus possible, knowledge gaps concerning the exact risks remain[1].

[1] At the time of writing, IATA just released that 3 manufacturers concluded their studies on the transmission risks (IATA, 2020). They found the risks to be low. These underlying data and methodology have been requested from the manufacturers and will be assessed once received.

The Ministry of Infrastructure and Water Management (IenW) assigned NLR and RIVM to assess the risk of transmission of SARS-CoV-2 in aircraft cabins based on a literature review, simulations and measurements. This resulted in CORSICA (**Co**ntamination **r**isk of **S**ARS-CoV-2 **i**n aircraft **ca**bins). CORSICA follows up on the previous 'HEPA-scan' by NLR that mapped the presence of HEPA filters on- board aircraft at the Dutch airports (Roosien, Peerlings, & Jabben, 2020).

1.2 Approach

In order to address the parliamentary motion, CORSICA looks for an answer to the following underlying research questions:

- What is the risk of SARS-CoV-2 transmission in aircraft cabins?
- What is the variance in viral emission by persons carrying the virus?
- How do viral particles spread through the cabin?
- What is the influence of cabin conditions on the transmission of the virus in the aircraft cabin?
- What is the role of cabin ventilation and filtration on the transmission of the virus?

NLR assesses the aeronautical aspects of the study as well as project coordination. RIVM is tasked with all health-related aspects of the study. The project consists of two distinct phases: (I) literature review and (II) simulation and measurements. The global time schedule is given in Figure 2.

This report is the deliverable of the literature review phase of CORSICA. The main aim of the literature review is to identify the most relevant parameters for SARS-CoV-2 transmission in aircraft cabins under the current corona guidelines. The findings of the literature review will be used as input for the measurement and simulation phase of the project.

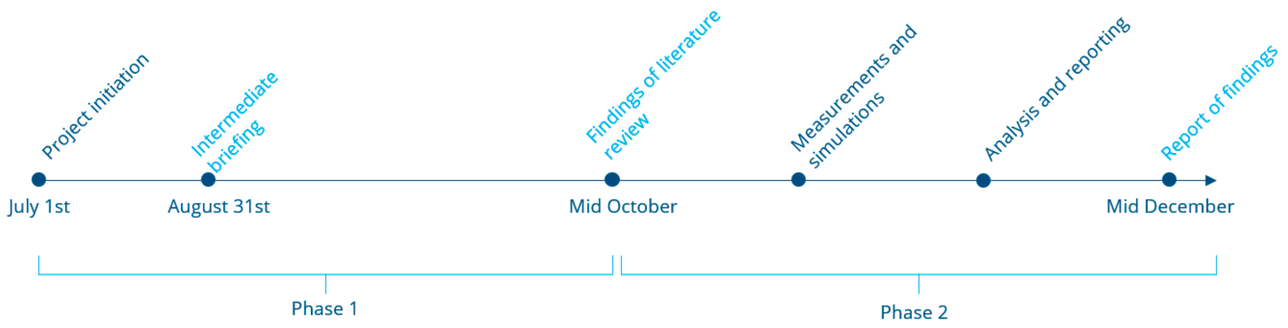

Figure 2: Project timeline, showing different phases and main deliverables

The second phase of CORSICA consists of measurements and simulations. The data resulting from the literature review will be complemented with data from the measurements inside aircraft cabins to inform simulation models for the spread of SARS-CoV-2 virus leading to an assessment of the virus exposure in a number of relevant scenarios.
The second phase of CORSICA consists of measurements and simulations. The findings and gaps of the literature review will be compared to simulation models and data available to the research group. A combination of measurements inside the cabin and simulations for the spreading of a virus will lead to an assessment of the virus exposure in a number of relevant scenarios.

1.3 Scoping and main assumptions

The study assesses viral transmission inside the aircraft cabin in line with the scoping of the assignment as described in Section 1.1. In aircraft cabins, unlike many other environments, it can be very difficult to observe the recommended 1.5 m distancing for prolonged periods of time (typically 2-10+ hours). On the other hand, the cabin environmental control system (ECS) ensures a high rate of cabin air refreshment by filtered air flow and environmental conditions such as temperature, humidity and pressure levels can vary, depending on the flight phase. The airport terminal and boarding bridges have different environmental conditions, layout, ventilation and possibilities for mitigating measures and are therefore excluded from the study.

Viruses can spread through a number of transmission routes. For this study the following routes are deemed relevant: direct transmission either through large droplets or aerosols, transmission through recirculated air, and transmission via contact with contaminated surfaces (further discussed in Chapter 5).

RIVM advised on the safety on board of aircraft in relation to SARS-CoV-2 and the associated safety protocols put in place by Dutch airlines, based on guidelines by EASA and ICAO. RIVM deems it plausible that the ventilation system on board of aircraft, with a high air exchange rate and vertical air flows, limits possible transmission of SARS-CoV-2 on board of aircraft. In addition to existing risk factors, adherence to these measures is an important factor in the risk of SARS-CoV-2 transmission in the aircraft cabin. Throughout the study the main assumption is that mitigation measures are enforced and complied with, unless explicitly stated otherwise. An overview of these mitigation measures and policy is prevented in Section 2.2.

1.4 Reader's guide

This report describes the main findings of the literature review of CORSICA. The findings are presented in the following chapters:

Chapter	Content	Aim
2	Information on SARS-CoV-2 in relation to aviation	Provide reader with background information on known cases and mitigation measures taken by the aviation sector
3	Information on relevant aviation processes, cabin systems, environmental conditions and different aircraft types	Provide reader with necessary background information about the aviation context and aircraft functioning, relevant to understand various viral transmission routes in aircraft cabins
4	Information about the source emitter such as emission characteristics and environmental effects on virus activation	Describe all relevant factors that would be part of assessment on contamination risk via simulation and measurements.
5	Relevant transmission routes in aviation cabins	
6	Information about exposure, such as dose-response relations	
7	Measurement and simulation	Provide an overview of considerations for the subsequent measurements and simulations in the next phase of the project
8	Conclusions on relevant parameters and their variation	Collect relevant input for second phase of project

In addition to describing the current state of knowledge, the chapters explicitly indicate any remaining knowledge gaps and possible strategies (such as performing simulation and/or measurements, anticipated in the next stage of the project) to fill these gaps.

2 SARS-CoV-2 and aviation

This chapter discusses SARS-CoV-2 in relation to aviation. Specifically, Section 2.1 discusses epidemiological evidence of transmission in aircraft cabins, and Section 2.2 describes mitigation measured currently used in aviation.

2.1 Epidemiological evidence of SARS-CoV-2 transmission in aircraft cabins

A number of studies concerning transmission of SARS-CoV-2 in aircraft have been published. All these papers examine flights in January, February and March 2020, which is partially due to the time it takes to trace passengers and receive their test results and partially due to the time it takes to write a scientific article. Papers concerning flights later in 2020 are expected to be published in the coming months. As only a small selection of flights have been examined and methodology differs per study (with or without comparison of genetic sequencing of virus, amount of passengers traced), the available literature cannot be used to draw conclusions concerning general statistics of SARS-CoV-2 transmission risk on board of aircrafts.

From Khahn et al., (2020) it is clear that passengers may become infected within a short distance of a symptomatic passengers and in absence of intervention measures on board. The flight from Hanoi to London took place at the beginning of March 2020 before interventions were in place. During the flight one passenger experienced complaints such as a sore throat and cough. In the business class cabin 20 passengers were seated which concerned a 75% occupation rate. Out of these 20 business class passengers 12 tested positive after the flight. They were seated within 2 meters of the index passenger. In economy class at least 2 out of the other 180 passengers became positive. Seating proximity was strongly associated with increased infection risk (risk ratio 7.3, 95% CI 1.2–46.2), and droplet or airborne transmission as the most likely route. Other studies also suggested virus transmission on board of aircrafts previously shown for other viruses as described below.

In March 2020, Yang et al. (2020) were the first to suggest likely SARS-CoV-2 contamination during flight, describing 10 positive cases amongst passengers who had all traveled on the same flight. Shortly after, Schwarz et al. (2020) described a case in which two COVID-19 positive passengers traveled on a long distance flight, but appear not to have infected any other passengers. Speake et al. (2020) describe a flight on board of which 11 passengers appeared to have been infected, a finding supported by comparison of viral gene profiles. An elevated risk is indicated/reported for passengers in window seats. Six other sources describe likely transmission of SARS-CoV-2 on board of an aircraft (Chen, et al., 2020; Eldin, 2020; Hoehl, 2020; Pavli, 2020; Choi, 2020; Lytras, 2020). Of these studies, only Choi and Speake use comparison of genetic sequences to support/prove in-flight transmission of SARS-CoV-2 to two crew members. Qian et al. (2020) report 11 infections among people having flow together, but could not identify the source of the infection.

Table 1 gives an overview of the published studies that could be reviewed by the authors at the moment of writing.

Table 1: Literature describing case studies of potential in-flight transmission of SARS-CoV-2, sorted by date of flight

Paper	Date of flight	Origin	Destination	Passengers COVID-19	Passengers likely infected during flight
Schwartz et al, 2020	22/01/2020	Guangzhou	Toronto	2	0
Yang et al, 2020	23/01/2020	Singapore Changi	Hangzhou Xiaoshan	12	10
Chen et al, 2020	24/01/2020	Singapore Changi	Hangzhou Xiaoshan	16	1
Eldin, 2020	25/02/2020	Bengui	Yaoundé	3+	One or more
Pavli, 2020	27/02/2020	Tel Aviv	Athens	6	5
Khanh et al, 2020	02/03/2020	London	Hanoi	16	15
Hoehl, 2020	09/03/2020	Tel Aviv	Frankfurt	9	2
Choi, 2020	10/03/2020	Boston	Hong Kong	4	2
Speake et al, 2020	19/03/2020	Sydney	Perth	29	11
Lytras, 2020	20/03/2020	London x 3	Athens	13	Not examined
Lytras, 2020	25/03/2020	Istanbul	Athens	2	Not examined
Qian et al, 2020	Unknown	Unknown	Zhejiang	11	10
Lytras, 2020	23/03/2020	Spain	Athens	25	Not examined

Experiences from before COVID-19

During the SARS-epidemic in 2003, aircraft transmission has also been documented (Olsen, et al., 2003). Olsen et al. note that illness in passengers was related to the physical proximity to the index patient[2]. Illness was observed in 8 of the 23 persons who were seated in the three rows (a distance of 2.3 meter) in front of the index patient, as compared with 10 of the 88 persons who were seated elsewhere. Olsen et al. note that airborne transmission may be an explanation for the observed pattern. Hertzberg & Weiss (2016), looking at 7 studies on aircraft transmission of SARS, influenza and measles, found that that on average ~6% of passengers seated within two rows of an infectious individual where infected. Beyond two rows from an infectious individual this dropped to ~2%.

Conclusions based on identified cases

The majority of these papers examine flights in January, February and March 2020. During this period ICAO and EASA had not yet published recommended mitigation measures to prevent viral transmission (see Section 2.2). Another factor is the time it takes to trace passengers and receive their test results and the time it takes to publish a scientific article. Studies of flights later in 2020 are therefore expected to be published in coming months and only then can we see the effect of the recommended mitigation measures by EASA and ICAO in the number of confirmed cases. As only a small selection of flights has been examined and methodology differs per study (with or without comparison of genetic sequencing of virus, number of passengers traced), the available literature cannot be used to draw conclusions concerning general statistics of SARS-CoV-2 transmission risk on board aircraft.

The studies provide epidemiological evidence that SARS-CoV-2 transmission can occur through air travel, but it was difficult or impossible to determine from these studies the precise transmission route (see Chapter 5) or whether transmission occurred in the aircraft or at the airport. From these studies, flight time, seat position (window or aisle) and proximity to the source emitter appear to be relevant factors for COVID-19 transmission on board of aircraft.

[2] The first person on board who is carrying the virus, the emission source

2.2 Mitigation measures used in aviation

The Dutch government states that the Dutch aviation sector takes measures to prevent the transmission of SARS-CoV-2 at airports and in aircraft cabins (Rijksoverheid, 2020). As indicated in Section 1.3, this study assumes that these mitigation measures are complied with.

These include the following measures:

- 1,5 m physical distancing wherever possible
- Additional attention to personal hygiene
- Stay at home when experiencing COVID-related symptoms
- Mandatory health statement for passengers
- Face masks at the airport and during the flight
- Aircraft with 'special ventilation' with a high air refresh rate
- Passenger registration in order to trace possibly contaminated passengers

These measures are based on EASA (2020) and ICAO guidelines. In addition to the measures mentioned above, the guidelines also call for:

- Inform passengers on the application of preventive measures on board and regularly remind passengers of said measures
- Reduced in-flight service
- Reduced use of gaspers to the maximum extent possible unless manufacturer specification states otherwise
- Use and regularly maintenance of HEPA-filters according to manufacturer specification
- Contact manufacturer for optimal ventilation setting (see Section 3.3 for more details)
- Ensure passengers are not kept on board without proper ventilation for longer than 30 minutes
- Use of all packs, APU-bleed or PCA is recommended (see Section 3.3 for more details)
- When allowed by passenger load, cabin configuration and aircraft mass and balance requirements, physically distance passengers as much as possible

The remainder of this section reflects on the known effects of the measures most relevant to passengers.

Facial masks

ICAO and EASA recommend that non-medical face masks are worn by passengers and crew during the entire flight except when eating or drinking. Mask wearing works in two ways, by preventing infected subjects from spreading droplets and aerosols, and by limiting exposure through inhalation. Filtering efficiency of masks will depend on the material of which the mask is made, fitting of the mask on the face, whether inhalation (exposure) or exhalation (emission) is considered and on the size of the emitted or inhaled particles or droplets.

Various studies on the efficiency of filtering of masks exist. Overall, the filtering efficiency of N95 masks is high, followed by that of surgical masks. Reported filtering efficiencies of these masks range from about 50% up to almost 100%. Cloth masks show more variability, with efficiencies ranging from below 30% up to about 90%, depending om material, particle size and fitting of the mask. According to Lelieveld et al. (2020), many studies have reported that facial masks substantially reduce the infection risk, which applies to disposable surgical masks as well as reusable cloth masks (Chu, et al., 2020; Esposito, Principi, Leung, & Migliori, 2020; Fischer, et al., 2020; Howard, et al., 2020; Leung, et al., 2020; 2020).

Verma et al. (2020) used aerosol visualization techniques to evaluate the effect of different mouth coverings on the dispersion of exhaled particles. Emulating emission during a single cough using a mannequin, the length of the exhaled particle jet was shown to be reduced from about 2.4 cm for the uncovered face to about 20 cm for the mannequin covered with a commercial face mask.

Filter efficiencies vary with the particle/droplet size and may be different for inhalation and exhalation. Howard et al. (2020) found that for 0.02 µm inhaled particles filter efficiencies for generally available household material masks were between 49% and 86%, whereas surgical masks had efficiencies of up to 89%. For the size range of particles between 0.02-1.0 µm, household materials had 3% to 60% filtration efficiency.

No studies for the efficiency of masks in aircraft cabins were found. For the modelling of COVID-19 transmission in aircraft we assume an inhalation filtering efficiency of about 30%, and a reduction in droplet and aerosol emissions of about 60% when masks are worn. This yields a total risk reduction of about 70% when all subjects in the room are compliant, in accord with the significant face mask efficacy derived by Cheng et al. (2020)*.*

Triage

To prevent infected passengers from boarding the aircraft as much as possible, passenger symptom and exposure screening at entry (so-called triage) is considered. Entry screening aims at assessing the presence of symptoms and/or the exposure to COVID-19 of travellers arriving from affected areas. Travelers that have been identified as exposed to or infected with COVID-19 should be quarantined or isolated and treated (Mouchtouri, Bogogiannidou, Dirksen-Fischer, Tsiodras, & Hadjichristodoulou, 2020).

A number of studies on the efficiency of symptoms/exposure-based screening has been conducted. These include modelling studies as well as observational studies. Modelling studies evaluate the probability of detection in different scenarios that typically represent different assumptions on uncertain, but highly critical factors such as the fraction of asymptomatic infected travellers and incubation period of COVID-19. Observational studies usually use a combination of symptoms/exposure-based screening, PCR screening and monitoring during quarantine. In such retrospective studies an estimate of the efficiency of symptoms/exposure-based screening can be made by comparing screening detection with retrospective observations on the development of disease. The available studies collectively suggest that the effectiveness of airport screening is limited. Best case estimates indicate a detection probability of up to about 50% for exit (i.e. pre-boarding) screening, but many estimates put the efficiency much lower, at below 10%.

As the likely number of infected persons on board is heavily dependent on epidemiological developments, this research will evaluate various scenarios with predetermined numbers of infected persons on board. These persons are assumed to be the only virus sources on board.

Aircraft disinfection

Following the mitigation measure that aircraft are disinfected regularly, the possibility of transmission from somebody on a flight to somebody else on a subsequent flight (e.g. through contact transmission) is excluded. This is consistent with the assumption in Section 1.3.

3 Understanding the aviation context

This chapter introduces the reader to the aviation context relevant to this research. This includes the flight process (Section 3.1), the cabin (Section 3.2), the workings of the cabin ventilation system (Section 3.3) and the cabin environment conditions (Section 3.4). Human factors relevant to cabin climate and air flows are discussed last (Section 3.5).

3.1 The flight process

This section describes the relevant aspects of the aviation process from the perspective of the passenger, the crew and the aircraft systems. As discussed in Section 1.3, the research focusses on the situation inside the cabin during passenger (de)boarding, taxiing and flight. Processes at the airport and outside the aircraft are out of scope for this study. The passenger process in the cabin is examined from the moment the passenger enters the aircraft, until the moment the passenger exits the aircraft. Throughout the flight, passengers are in close proximity to one another.

Passenger boarding

Passenger boarding typically starts 25 to 60 minutes prior to departure, depending on the number of seats. Especially for flights with a longer flight time (intercontinental, long haul) passengers might be called for boarding in groups depending on their seating position in the aircraft. With most shorter flights, passengers board in a random order. Business or first-class passengers or passengers with disabilities or small children might receive priority when boarding depending on airline policy. On board the aircraft, passengers walk along the aisle to their designated seat[3]. When walking along the aisle (or waiting for other passengers), when sitting down and when stowing luggage, passengers are often in close proximity to one another. In the meantime, the cabin crew is preparing for take-off or managing the boarding process. Fresh air is provided by a pre-conditioned air unit (PCA) through the aircraft's environmental control system (ECS). When a PCA is not available, fresh air can be supplied by the aircraft's auxiliary power unit (APU).

Taxi, take-off, climb, descent and landing

During taxiing, (the first phase of) take-off, climb and (the last phase) of descent the 'seatbelts fastened'-sign is on and both passengers and cabin crew are in their designated positions. Fresh air is provided through the aircraft environmental control system (ECS), powered by the aircraft's main engines or via a dedicated electric compressor (currently only the Boeing 787). Schuchardt et al. (2019) measured higher CO_2 concentrations during taxi and take-off, which they ascribe to a lower air exchange rate during these flight phases.

Cruise

For aircraft journeys over 1,5 hours, the cruise phase has the longest duration. Passengers generally spend most of the cruise in their allocated seat. At this point, the passenger is mainly exposed to the passengers seated in close proximity. If the 'seatbelts fastened'-sign is off, passengers may get up from their seat to walk about or visit the lavatory. This often results in close contact between passengers, both in the same row and along the aisle. Nevertheless, this is generally less erratic than boarding (and disembarking) process. On longer flights one or multiple meals or refreshments might be served by the cabin crew. This might result in close contact between passengers and cabin crew. During meals or drinks, passengers are exempted from wearing masks.

[3] Most airlines provide passengers with an assigned seat. Some low-cost airlines used to let passenger pick their own seat when boarding the aircraft. No examples of this practice were found today.

Disembarking

When the 'seatbelts fastened'-sign turns off, passengers may get up to retrieve their overhead luggage and to get off the aircraft. This may result in close contact between passengers, especially if the process is not managed by the cabin crew.

Boarding and disembarking are the phases which present the most diverse and close contacts between passengers, in which passengers interact with several other passengers and crew members. Therefore, these are relevant parts of the passenger process to be considered in this study. The taxi-in/out is considered to be relevant because of the duration and possibly lower air exchange rate. The cruise is considered to be relevant because of the nominal airflows, duration and the possibility for passengers to freely move around the aircraft.

Table 2 summarises the broader flight process, including crew and aircraft state and the fresh air source.

Table 2: Overview of the passenger, cabin crew and aircraft process, as well as the fresh air source, over different phases of the flight. PCA refers to pre-conditioned air; APU to auxiliary power unit

Flight phase	Passenger	Cabin crew	Aircraft	Fresh air source
Boarding	Walking, standing, seated	Guide boarding process	APU powered	PCA / APU
Taxi	Seated	Final checks, safety instruction, or seated	Engines on (mostly idle)	Main engines (bleed air[4])
Take-off and climb	Seated	Seated until seatbelt sign off	Engines on (high thrust), cabin pressurised via ECS	Main engines (bleed air[4])
Cruise	Seated, in aisle or in lavatory	Standing and walking, galley or aisle	Stable cruise conditions	Main engines (bleed air[4])
Descent and landing	Seated	Final checks or seated	Engines on (low thrust), engines cool off during taxi-in	Main engines (bleed air[4])
Disembarking	Seated, standing, walking	Guiding disembarking	Engines off	PCA / APU

3.2 The aircraft cabin

From the perspective of the cabin one can divide aircraft in two main types: single aisle aircraft (also called narrow-bodies) and twin aisle aircraft (also called wide-bodies). This section describes the main relevant characteristics of both.

Single aisle aircraft

Single aisle aircraft, such as the Airbus A320 and Boeing 737 models, are mainly used for short and medium range flights. They are typically equipped with three seats on either side of the aisle. Regional aircraft, such as the Embraer E175 and E190 models, have a narrower fuselage and as such feature less seats per row. Lavatories (toilets), galleys (kitchens) and other so-called cabin monuments are generally located at the front and rear of the cabin. Some operators offer a business class product in their single aisle aircraft. Most of the times this is the case, the business class is separated from the other sections by a small curtain. Larger and more luxurious business class seats, used in

[4] For Boeing 787: separate air compressor. Further details in Section 3.1.

long-range aircraft, are only used by some operators. Instead, others leave the middle seat (in each block of three) unoccupied, to provide passengers with additional space.

Cabin dimensions vary from aircraft to aircraft. The most produced single aisle aircraft (Airbus A320 and Boeing 737 families) have a cabin width between 3.5 and 3.7 metres and a maximum height of approximately 2.10 metres. Many aircraft are produced in different fuselage lengths, with one such group of derivative models designated as 'family'. For the aforementioned aircraft models, this means that the cabin length ranges between approximately 21 and 35 metres. As the number of seats per aircraft also increases if the cabin is lengthened, the floor area per seat remains approximately constant. For the single aisle types considered here, this typically ranges between approximately 0.5 and 0.6 square metres.

In economy class, average seat pitch 81 centimetres and average seat with is approximately 44.5 centimetres in single aisle aircraft (SeatGuru, 2020)*. In business or first class, seat pitch is about 100 centimetres and width is almost 51 centimetres* (SeatGuru, 2020)*. Regulations set a minimum aisle with of 51 centimetres at seating level* (EASA, 2020)*. This means that, measured from the centre of an economy middle seat in a six-abreast cabin (seat 1 in Figure 4), the centre of 9 other seats is located within 1.5 metres. For a window seat (2), this number decreases to 8 other seats. For an aisle seat (3), 12 seats are within 1.5 metres. For the business class section, the number of seats within 1.5 metres will be lower due to the larger seat pitch and width.*

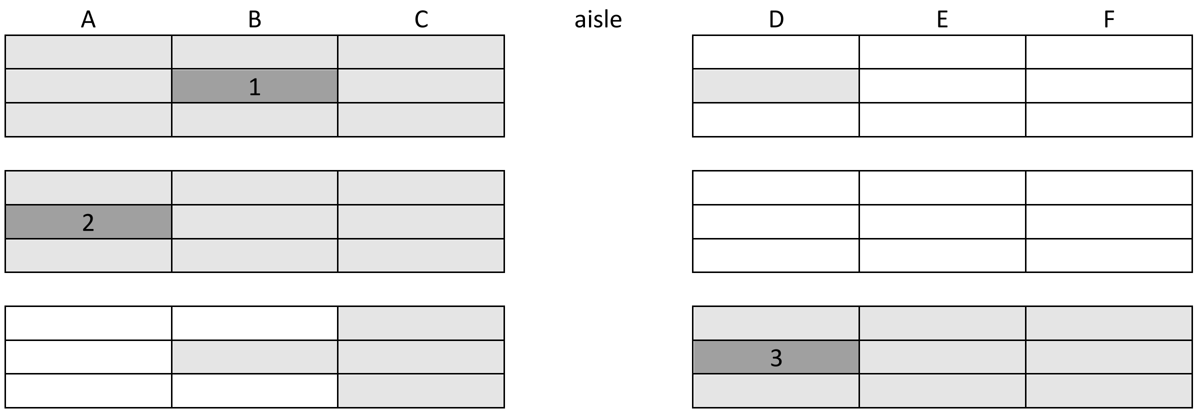

Figure 3: Schematic single-aisle (6-abreast) economy class cabin layouts. Colours indicate the number of seats (light grey) within a 1.5 metres distance of an index middle (1), window (2) or aisle (3) seat (dark grey)

Twin aisle aircraft

Twin aisle aircraft, such as the Airbus A330 and A350, and Boeing 777 and 787 models, are used for intercontinental flights. Contrary to the single aisle aircraft, they generally are equipped with more distinctly separated travel classes (e.g. first class, business class, economy comfort or premium economy, and economy). Lavatories, galleys and other cabin furnishings are used to provide physical barriers between different cabin segments.

As the cabin width of twin aisle aircraft varies more than that of twin aisle aircraft (for the aforementioned models, between about 5.3 to 5.9 metres), the number of seats per row also varies. The economy class section of a Boeing 777 often has 10 seats across in a 3/4/3-layout, whereas the Airbus A330 and Boeing 787 are typically limited to 8 or 9 seats per row. In other travel classes such as business or first, larger seats are used, leading to less seats per row and more space per passenger.

Compared to single aisle aircraft, the cabin of twin aisle aircraft is also higher, with typical maximum values between 2.2 and 2.5 metres. Again, aircraft come in longer and shorter variants. For the four models considered here, the cabin length varies between approximately 40 and 60 metres. Data shows seat width and pitch in twin-aisle economy cabins is very similar to seat width and pitch in single-aisle economy cabins (SeatGuru, 2020). *That means that for a 3/4/3-layout, the number of (centres of) seats within 1.5 metres from (the centre of) a specified seat is comparable: 9 for a middle seat in a block of three adjacent seats (1 in Figure 5), 13 for either 'middle' seat in a block of four seats (2), 8 for a window seat (3) and 13 for an aisle seat (4). Again, these numbers will be lower in more luxurious travel classes (premium economy, business or first). Due to the larger variation in cabin arrangements, typical values could not be reliably determined.*

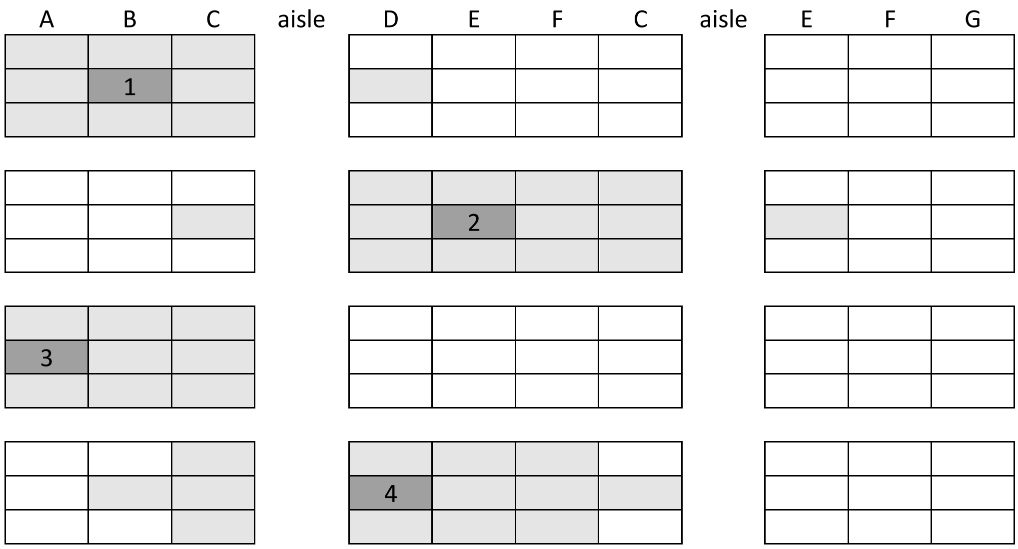

Figure 4: Schematic twin-aisle (3/4/3-layout) economy class cabin layouts. Colours indicate the number of seats (light grey) within a 1.5 metres distance of an index middle (1 and 2), window (3) or aisle (4) seat (dark grey)

Occupancy rates

Occupancy rates (or: passenger load factor) on passenger flights to and from the Netherlands was between 75 and 85% in the period January to May 2019 (CBS, 2020). From March 2020, this decreased to an average of 40% in the period of March to May 2020 (CBS, 2020). August passenger load factors in Europe[5] are 63.5%, 25.5%-points below the same month in 2019 (IATA, 2020).

3.3 Environmental control system

The cabin environment is controlled by the environmental control system (ECS) of the aircraft, which is deemed a relevant factor for the transmission risk on board of aircraft. Among others, the ECS maintains a comfortable cabin pressure, temperature and humidity and provides a constant supply of fresh air.

[5] Detailed information for the situation in the Netherlands after May 2020 is not available.

3.3.1 System architecture

The ECS is a complicated system that ventilates the cabin using a mixture of fresh outside air and recirculated cabin air. On a high-level, the ECS consists of an exterior air inlet, a mixing manifold, cabin air inlets, cabin air outlets, recirculation systems and an exterior air outlet. The system components are discussed in further detail in the following sections, where ECS operation under cruise conditions is assumed. Conditions whilst on the ground are discussed separately.

Inflow of outside air

Outside air is typically sourced from one of the compressor stages of the engines (so-called bleed air)[6]. Incoming air is treated before being send to the mixing manifold by ozone converters to lower dangerous levels of ozone and brought to the right temperature and pressure in so-called ‘packs’ (pneumatic air cycle kits). Most aircraft have two packs (for redundancy and performance reasons) (Tao, Meng, Liping, & Jun, 2011; Hunt, Reid, Space, & Tilton, 1995).

The probability of active viral particles in outside air is assumed zero.

Mixing manifold

The mixing manifold mixes the conditioned outside air from the packs with recirculated, filtered air from the cabin. According to generic literature on aircraft cabin environmental control systems, the ratio between fresh outside air and recirculated air is approximately 50:50 (Moir & Seabridge, 2008; Hunt, Reid, Space, & Tilton, 1995).

The ratio between outside and recirculated air could not be verified using operators or manufacturers’ information. As such, this will have to investigated in further research phases, for example by the use of measurements.

Cabin air flow

The air mixture from the manifold is supplied to the cabin using various inlets near the top of the cabin and extracted through air outlets near the floor. Inflow and outflow volumes are generally balanced over the length of the cabin, reducing the spread of particles in lengthwise direction. Various strategies for air inflow, distribution and outflow exist (Zhang, Liu, Pei, Li, & Wang, 2017; Elmaghraby, Chiang, & Aliabadi, 2018; You, Lin, Wei, & Chen, 2019). Most aircraft utilise so-called mixing ventilation (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002) where air continuously enters and exits the cabin. Elmaghraby et al. (2018, p. 163) note that the mixing ventilation strategy helps to “dilute and disperse infectious organisms and contaminants within the cabin”, thereby lowering concentrations.

In addition to the centralised inflow channels, many aircraft provide personalised ventilation in the form of overhead gaspers (shown in Figure 6). Passengers may turn the gaspers to adapt the mass flow and direction of the air from the gaspers to reach their direct environment. It is argued that such personalised air streams can further reduce the spread of contaminants from sources inside the cabin entering the breathing area of other passengers. However, other sources note that the gaspers sometimes supply air directly extracted from the cabin, and thereby not mixed with fresh air from outside the aircraft, although it is filtered using a separate filter, “similar to the filter for recirculated air” (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002, p. 61). Furthermore, the interaction of flow from the gaspers and flow from other (non-personalised) inlets can cause turbulence. Overall, air predominantly flows from top to bottom, there is however some randomness associated to the movement of air in the aircraft cabin (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002, p. 45).

[6] The Boeing 787 is currently the only exception to this, as that aircraft has a separate compressor for outside air

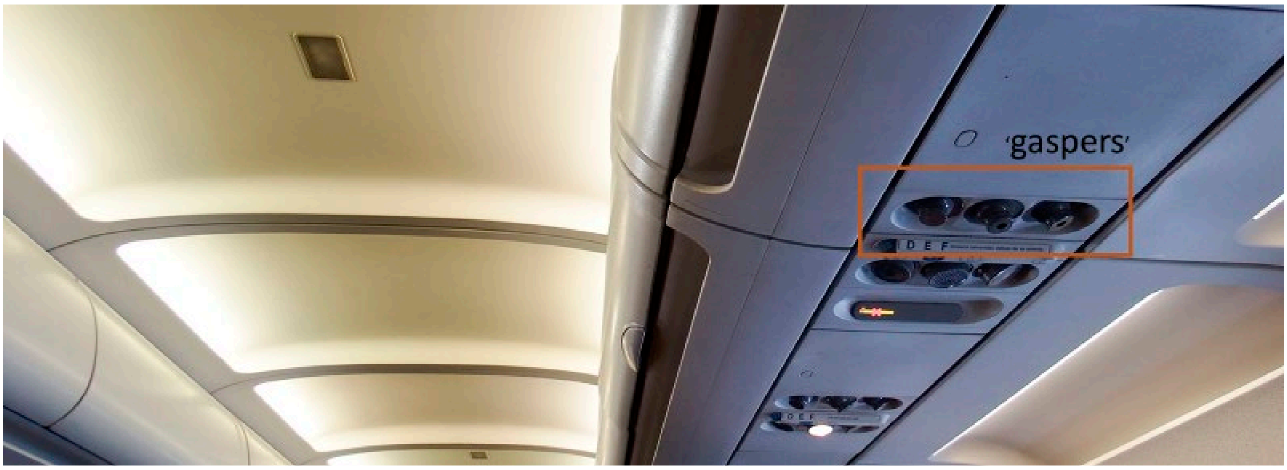

Figure 5: Overhead gaspers in Airbus A320 (NLR, n.d.)

The exact flow patterns throughout the cabin are not documented in publicly available information and are to be determined using simulations in measurements in the following phase of this research. In addition, the exact configuration of the environmental control system (or details thereof) of selected aircraft types for subsequent simulations and/or measurements will have to be determined.

Recirculation system

Approximately 50% of the outflowing cabin air is cleaned and then recirculated through the mixing manifold. Most aircraft operated to and from Amsterdam Airport Schiphol clean the recirculated air by High Efficiency Particulate Air (HEPA) filters (Roosien, Peerlings, & Jabben, 2020). Depending on the specification of the filter, these filters remove the vast majority of small particles. The number of filters per aircraft type varies, with typical models having anywhere between one and ten filters (Michaelis & Loraine, 2005).

Exterior outlet

The remainder of the cabin air that is not recirculated is expelled overboard through the outflow valve. Literature suggests that the air drawn from some cabin sections (such as galleys and lavatories) is expelled overboard directly, in order to prevent contaminating the recirculated air flow with, for example, unpleasant odours (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002). The outflow valve is typically located to the rear of the fuselage, with larger aircraft often also having one near the middle of the fuselage.

The currently reviewed literature could not be used to unambiguously conclude that the air of particular cabin areas is not recirculated. Manufacturer or operator information, or measurements, will be used to determine this.

On the ground

When the aircraft is on the ground and its main engines are not running, the APU can be used to supply conditioned air (as well as pneumatic and electrical power). The APU provides air in a similar method as the main engines.

In order to reduce noise and emissions while on the ground, aircraft operators are stimulated to use the pre-conditioned air (PCA) supplied from ground-based airport equipment instead of the APU. These normally connect downstream of the air conditioning pack and directly supply conditioned air to the mixing manifold. When the difference between outside and (desired) inside temperature is large, the APU might be used to provide additional cooling or heating capacity. In addition, literature notes the possibility of high-pressure ground cart air to be supplied to the packs directly (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002).

3.3.2 Performance and certification

The frequency at which the cabin air is exchanged varies per aircraft. Values range between approximately 10 to 30 times per hour (Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002; IATA, 2018; Hunt & Space, 1994; Hunt, Reid, Space, & Tilton, 1995). Air supply is to some extent regulated by means of airplane certification specifications that have to be met before a type certificate is awarded to an aircraft, which is required for passenger operation. Furthermore, various associations have developed non-enforceable standards.

Certification specifications

Air supply per passenger is regulated by various authorities (Rydock, 2008). Both the FAA (FAR 25.831) and EASA (CS 25.831) note that "for normal operating conditions, the ventilation system must be designed to provide each occupant with an airflow containing at least 0.25 kg [0.55 pounds] of fresh air per minute" (EASA, 2020; U.S. Government Publishing Office, 1996). At a cabin pressure altitude of 8000 ft[7] and a cabin temperature of 24 °C, this is equivalent to 10 cubic feet per minute (4.7 litres per second). At the cruise conditions specified in Section 3.4, 0.25 kilogram per minute is equivalent to 0.267 m^3 per minute, or 4.4 L/s.

Compliance to this requirement can be shown by "averaging the total cabin fresh air supply and cockpit fresh air supply for the number of occupants that each area can accommodate, assuming a uniform ventilation distribution in each area" (EASA, 2020, AMC 25.831(a), par. 1). In case a type certificate applicant (i.e., aircraft manufacturers) "proposes not to provide the minimum required fresh airflow during the phases of flight that use low power levels, the applicant must show that the cabin air quality is not compromised during those flight phases" (EASA, 2020, AMC 25.831(a), par. 2).

Neither standard sets limits to the airflow of recirculated cabin air. EASA (2020, AMC 25.831(c)) *however stipulates that it "should be possible to stop the recirculating system and still maintain the fresh air supply prescribed".*

Other standards

In addition to these certification specifications, the ANSI[8]/ASHRAE[9] Standard 161-2018 on air quality within commercial aircraft notes the below standards for aircraft in flight, per person (ASHRAE, 2018). Compliance with these standards is not enforced by law and not guaranteed. Nevertheless, similar (or better) figures are found in publications by Boeing (Hunt & Space, 1994; Hunt, Reid, Space, & Tilton, 1995):

- A minimum outside air supply of 7.5 cubic feet per minute (3.5 L/s), assuming a ventilation effectiveness[10] of at least 1;
- A minimum total air supply of 15 cubic feet per minute (7.1 L/s), and a recommended minimum total air supply of 20 cubic feet per minute (9.4 L/s);
- A minimum airflow capacity of personal airflow outsets of 2 cubic feet per minute (0.94 L/s);
- A minimum outside air supply of 7.5 cubic feet per minute (3.5L/s) and a minimum total ventilation air supply of 20 cubic feet per minute (9.4 L/s) to crew rest stations;
- A minimum ventilation airflow (outside air, recirculated air, adjacent cabin air or combinations between these) of 20 cubic feet per minute (9.4 L/s) to occupied lavatories.

[7] Cabin pressure is often expressed in terms of pressure altitude. A cabin pressure altitude of 8000 ft indicates the pressure inside the cabin is equivalent to the pressure outside at 8000 ft (approximately 2500 metres).
[8] American National Standards Institute.
[9] American Society of Heating, Refrigerating and Air-Conditioning Engineers.
[10] Ventilation effectiveness is "defined as the fraction of the outside air delivered to the space that reaches the breathing zone – the region within the occupied space that is located between planes 3 in. (75 mm) and 72 in. (1830 mm) above the floor and 2 or more in. (50 or more mm) from the wall" (ASHRAE, 2018, p. 3).

For aircraft on the ground, not using on-board systems, a minimum of 20 cubic feet per minute per person (9.4 L/s) is prescribed. In case on-board systems are used, minima are set at 7.5 cubic feet per minute (3.5 L/s) of outside air and 15 cubic feet per minute (7.1 L/s) of total air per occupant, calculated on a bulk average basis.

Verified information about air exchange frequencies and/or (total or per passenger) air supply could not be established from literature reviewed. As such, this will have to be determined using measurements. Alternatively, adherence to aforementioned standards could be verified (e.g. with manufacturers or operators), such that these can be used in the modelling steps. Actual aircraft characteristics might however differ from such design specifications, for example due to wear, or product changes applied during the operational life.

Certification of HEPA-filters

HEPA filters are classified by the percentage of removed small particles with a particular diameter. In case of the European NEN-EN 1822 norm, this most penetrating particle size (MPPS) is determined from experiment. In case of the American MIL-STD 282 (Revision B, 2015) norm, the MPPS is set at 0.3 micrometres.

The NEN-EN 1822 norm applies to high efficiency particulate and ultra-low penetration air filters (EPA, HEPA and ULPA). HEPA-filters come in two classes (H13 and H14), with an integral MPPS-efficiency of at least 99.95% and 99.995%, respectively (NEN, 2019, Sec. 6.5). Filtration performance is assessed based on the testing methodology laid out in the method. A number of testing aspects are deemed relevant:

- The air in the test channel used for testing shall have a temperature of (23 ± 5) °C and a relative humidity lower than 75% (NEN, 2019, Sec. 7.2).
- During the test procedure, temperature and relative humidity shall remain constant within ± 2°C and ± 5%, respectively (NEN, 2019, Sec. 7.2).
- The MPPS shall be determined from the efficiencies determined for a range of particle sizes at the nominal filter medium velocity (NEN, 2019, Sec. 7.4).
- The filter shall be marked with the nominal air volume flow rate at which the filter has been classified (NEN, 2019, Ch. 9). The effectiveness of filters may depend on the nominal air volume flow rate.

NEN EN-1822 stipulates that the filter element shall be designed or marked so as to prevent incorrect mounting (NEN, 2019, Sec. 6.2).

Revision B MIL-STD 282 is not publicly accessible. According to secondary literature, MIL-STD 282 Method 102.9.1 specifies a HEPA filter must capture a minimum of 99.97% of contaminants at 0.3 microns in size (DD Group; Donaldson Filtration Solutions; Committee on Air Quality in Passenger Cabins of Commercial Aircraft, 2002). This size is selected as it “approximates the most difficult particle size for a filter to capture” (Donaldson Filtration Solutions).

Since the late 1990’s, HEPA-filters meeting the MIL STD 282, 99.97% efficiency requirement, have been installed on Boeing 737, 747, 757, 767 and 777 aircraft, and have been available for retrofit for aircraft delivered earlier. The Boeing 787 has been delivered with HEPA/APS filters since delivery in 2011. Airbus aircraft have been equipped with HEPA-filters from 1994. Research on flight movements to and from the five largest airports in the Netherlands in 2019 showed 99.1% of aircraft was equipped with an HEPA-filter (Roosien, Peerlings, & Jabben, 2020).

The classification and particular properties (e.g. nominal filter medium velocity, MPPS and other tested particle sizes) of HEPA-filters used on board of commercial aircraft could only be retrieved to a limited extent. As such, the effectiveness of HEPA-filters could not be unambiguously determined based on the currently publicly available literature reviewed.

The installation and/or use of HEPA-filters is not part of the airworthiness certification standards for commercial aircraft (EASA, 2020).

Maintenance of HEPA filter

HEPA filters are generally replaced during the C-check. The C-check is an elaborate maintenance check, which must be performed at an interval specified by the aircraft manufacturer. For most aircraft, the C-check is prescribed every 4000 – 6000 flight hours. If a HEPA filter is not replaced for a longer period than specified, air flow will be reduced, but the filter will not become less effective at removing viruses and bacteria. According to IATA, most airlines change the HEPA filter more frequently than prescribed (IATA, 2018).

3.3.3 User settings and controls

The pilots can control the components of the ventilation and pressurisation architecture, generally in the following manner:

- **Recirculation or cabin fans**
  The pilots can individually switch the two recirculation fans (or: cabin fans) on and off. During regular operation, both fans are active. The only reason to switch off a fan during flight is a technical failure or a special procedure.
- **Packs**
  Both packs can be individually controlled. There are three settings: AUTO, OFF and (for some aircraft) HIGH. During normal operation, both packs are set to AUTO, which means they are active. The pilot will only switch off a cooling pack in case of failure. The HIGH setting is meant to be engaged only if one cooling pack has been switched off. Pack outlet temperature is controlled via the master temperature settings.
- **Trim valves**
  The pilot indirectly controls the trim valves via temperature settings. The higher the master temperature, the more open the trim valve will be.
- **Outflow valve**
  In automatic mode, the pilot indirectly controls the outflow valve by setting the cabin altitude controller. This translates to an outflow valve setting to maintain desired cabin pressurization at a certain altitude. It is possible for the pilot to regulate cabin pressure manually by manipulating the outflow valve position; the more open, the lower cabin pressure becomes.

3.4 Environmental conditions

This section gives an overview of the main environmental conditions inside the cabin.

Temperature

Temperature inside the cabin can be controlled from the flight deck by the pilots and, in some types, by the cabin crew from the cabin. A 2012 Harvard study (Spengler, Vallarino, McNeely, Estephan, & Sumner, 2012) that monitored on cabin temperatures during flights showed:

- Average: 24.4°C ± 2°C
- Min-Max: 19-31°C.

On long and medium duration flights a mean of 23.9°C and on short duration flights 24.8°C was found. Another study shows us environmental data from 7 intercontinental and 24 continental flights, this data has been plotted against flight time. Temperature during the flight does fluctuate, but the data reveals no link between temperatures in different stages of the flight. For most intercontinental flights, temperatures are between 21 and 26°C, while most continental flights show temperatures between 24 and 28°C (Liping, Yue, Dong, & Meng, 2014).

Temperatures in the aircraft cabin while still on the ground have not been found to be described extensively in literature. In order to determine temperatures on the ground, measurements may need to be done in an operational setting.

Pressure

With increasing altitude, the outside atmospheric pressure as well as partial pressure of oxygen decreases. EASA CS 25.841 regulation states that during climb pressure in the aircraft cabin is allowed to gradually decrease with altitude up until a cabin pressure altitude of 2348 metres[11] at the maximum operating altitude. A Harvard study on cabin pressure showed:

- Average: 800 hPa ± 28 hPa
- Min-Max: 780-885 hPa

Minimum, mean and maximum values for the Boeing 737-700 and the Boeing 777 were 760-782-809hPa and 770-794-885hPa respectively (Spengler, Vallarino, McNeely, Estephan, & Sumner, 2012). Another study, using 7 intercontinental flights showed similar values. The pressure during cruise flight lay between 776hPa and 850hPa (Liping, Yue, Dong, & Meng, 2014). On the ground, during boarding, cabin pressure is practically the same as the outside ground level pressure. After boarding, during the taxi phase pressure can be increased slightly (< 10 hPa).

Pressure averages and ranges in the aircraft are well described in literature. Found literature can be used to determine specific inputs for modelling. When necessary, for pressures at specific points during the flight may be determined in measurements.

Relative humidity

Relative humidity is the percentage of water vapour in air with respect to the saturation level at a specific temperature. Warm air has a high absolute saturation level, while cool air saturation levels are lower. During the first phases of the flight up to the cruise altitude the outside air temperature decreases, lowering the amount of water vapour in one kg of air substantially. Thus, aircraft take in very cold outside air, subsequently heat it, and the relative humidity can become very low. In a Harvard study (Spengler, Vallarino, McNeely, Estephan, & Sumner, 2012) it was found that in-flight cabin humidity values were:

- Average: 11% ± 5%
- Min-Max: 1.7-41%

In one study it was found that relative humidity starts out between 15% and 60% at the start of the flight and decreases with time to a value between 10% and 30% (Liping, Yue, Dong, & Meng, 2014). The last phase of the flight shows an upward trend back to around 30%. On the ground, as outside air is drawn into the aircraft, relative humidity conditions are as well strongly dependent on the outside air temperature and humidity.

Relative humidity levels on ground should be measured as there is no conclusive literature found describing relative humidity during this flight phase.

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[11] See footnote 7 on page 24.

Gravity and acceleration

Gravity is pointed towards the centre of the earth. This means that when an aircraft has a positive pitch (upward angle of the fuselage with respect to the horizon), gravity will not pull objects straight down onto the floor, but will have an additional small longitudinal component along the fuselage. During the climb phase aircraft have the highest pitch. The longitudinal component of gravitational acceleration may be as high as 1.7 to 3 m/s^2 (depending on the pitch angle), while the vertical component lies between the 9.6 and 9.3 m/s^2. In other flight phases the pitch angle is usually much lower, significantly decreasing the horizontal component of gravitational acceleration. The effect during cruise is likely small, due to low pitch. Accelerating the aircraft, especially during take-off and climb and turns, has similar effects on the airflow and path of particles in the aircraft cabin.

The effects of gravity and acceleration on the distribution of different types of particles have not been quantified. As such, this effect should be investigated using experiments.

3.5 Human factors

The technology and operational use of the environmental control system is important for the air flow dynamics in the aircraft cabin, but the flow can be significantly influenced by presence and actions of humans. This paragraph describes possibly relevant human factors that might influence transmission of the virus.

Body temperature (vertical gradient)

Passengers are a source of heat, emitting roughly 75 – 100 Watt dependent on body size. The heat emitted by the humans will partly travel up towards the ceiling due to hot air convection, causing a vertical temperature gradient. In combination with the downward flow of air towards the outflow ducts, the temperature gradient is expected to increase turbulence.

Thermodynamics could be incorporated into the simulation to account for the body temperature effect.

Flow obstruction

Humans, whether seated or standing, obstruct air flows as they would be in an empty cabin. Especially their legs around the outflow duct alter flows at floor level. The placement of passenger belongings can also obstruct flows, for example by blocking (parts of) outflow ducts under seats.

Air flows including the presence of passengers will be represented in the model as much as possible. Using (model) humans in measurements is advised.

Breathing (temperature and turbulence)

Humans continuously breathe. By doing so, they emit puff clouds; warm and moist air. The puff clouds cause turbulence in the air flows at head level due to their direction (usually towards the front of the aircraft) and temperature.

Gasper use

As mentioned in Section 3.3.1 passengers are in control of their own personal ventilation via gaspers, if these are installed. They can control the direction and force of air flow from their personal gasper. This influences flows at head level.

As passengers are in control of their own gasper, it is difficult to incorporate this into a simulation of cabin air flows. A general assumption can be made; for example, that two gaspers are on per row, and in a certain direction.

Movements (advection)

When passengers or crew move through the aircraft, they generate air flows with their slip stream and push forward an air column. The movements also induce extra turbulence. In an aircraft this is mainly relevant for movement of particles in the aisle. During boarding and disembarking, when many passengers move along the aisle, this effect is greatest. During cruise, a passenger or crew member moving down the aisle can transport particles through the aircraft between sections or rows.

4 Emission source

This chapter gives an overview of the main findings and remaining knowledge gaps related to the source emitter (the person carrying the virus).

4.1 Viral characteristics SARS-CoV-2

In January 2020 Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2, also known as Corona-virus or 2019-nCoV) was identified as the causative agent causing the disease COVID-19 (Gorbalenya, et al., 2020). The SARS-CoV-2 virus, like SARS-CoV and MERS-CoV, is a coronavirus belonging the family *Coronaviridae* and to the genus beta-coronavirus. It is an enveloped, positive-sense, single-stranded RNA virus of 50-200 nm in diameter, and the genome is approximately 30 kb in length. Like other coronaviruses, SARS-CoV-2 has four structural proteins, known as the S (spike), E (envelope), M (membrane), and N (nucleocapsid) proteins. The spike protein is the protein responsible for allowing the virus to attach to and fuse with the ACE2 receptor on the membrane of a host cell. By 22 January 2020, the full virus genome was unravelled (Zhou, et al., 2020). Since then multiple variants have been distinguished however data on the quantities of SARS-CoV-2 in human airtracts and in the air are scarce so no distinction is made between different virus variants.

COVID-19 is a mostly respiratory disease with virus excreted in respiratory and oral secretions by coughing and sneezing and also by singing, talking and breathing. SARS-CoV-2 can also be excreted in stools and is readily inactivated by e.g. alcohol. SARS-CoV-2 infections can also occur without symptoms and can be excreted in the absence, and prior to the development of symptoms.

4.2 Physical properties of aerosols containing SARS-CoV-2

When humans infected with COVID-19 exhale, they will likely emit aerosols containing the SARS-CoV-2 virus. This paragraph describes the physical properties of these aerosols.

Characteristics and travel distance of aerosols in exhaled air

Humans can produce droplets ranging in size from <1 – 2000 μm during expiration events. Schijven et al. (2020) describe different datasets from the literature on small droplet production during breathing, speaking, coughing and sneezing. Droplet geometry is assumed to be spherical, which is also assumed by Papineni and Rosenthal (1997). The droplets consist of water, salts and organic matter, including viruses.

Liu, Wei, Li and Ooi (2017) provide data on how the travel distance of a respiratory droplet is influenced by residue size, relative humidity (RH), and turbulence. They assumed that the initial concentration of sodium and potassium chloride in a respiratory droplet equals 150 mM, similar to the concentration in plasma. The solid part of a respiratory droplet including all of the suspended mucous organics and potential pathogens is assumed to be insoluble solids. The density of the solids is assumed to be 2000 kg/m3, and the specific heat capacity is 1000 kJ/ (kg °C). The initial solid volume ratio is 1.8% according to Duguid (1946). The sodium chloride and potassium chloride dissolved in respiratory droplets have very strong hygroscopicity, and they tend to absorb vapor from the ambient air. In dry air, when droplets evaporate to their droplet nuclei sizes, the insoluble solids and non-volatile solutes form a crust that is assumed to be spherical, and the droplet nuclei size is the size of this crust.

Relative humidity can affect aerosol size and thus deposition speed, as well as potentially virus inactivation due to drying. In general, larger droplets produced by coughing that are >60 µm fall to the ground quickly within 1.5 meter, while small droplets <20 µm stay airborne. Droplets produced by coughing <60 µm r in size can either deposit (at higher relative humidity), or evaporate and become airborne droplet nuclei (at lower relative humidity) (Liu, Wei, Li, & Ooi, 2017)

Droplets with an initial diameter of 60 µm can reach a horizontal distance of about 4 m, evaporating to 0.32 times its initial diameter at a relative humidity (RH) of 0%. At a RH of 90%, a droplet with an initial diameter of 60 µm can travel a distance of 1.85 m due to its larger size of 0.43 times the initial diameter (Liu, Wei, Li, & Ooi, 2017). In the case of directed air flows, even initially larger particles are likely to be able to travel even further. Liu, Wei, Li and Ooi (2017) (2017) presented a model to predict mass loss of droplets as a function of relative humidity.

Aerosol size distributions and numbers

Schijven et al. (2020) describes size distribution and numbers of aerosol droplets produced during different modes of exhalation, namely sneezing, coughing, speaking and breathing. An overview of the resulting total aerosol droplet volume that is produced, is shown in Figure 7 7. For transmission modelling, size distributions and numbers of the aerosols will be same as in this study, implying low and high scenario's for breathing, speaking, coughing and sneezing.

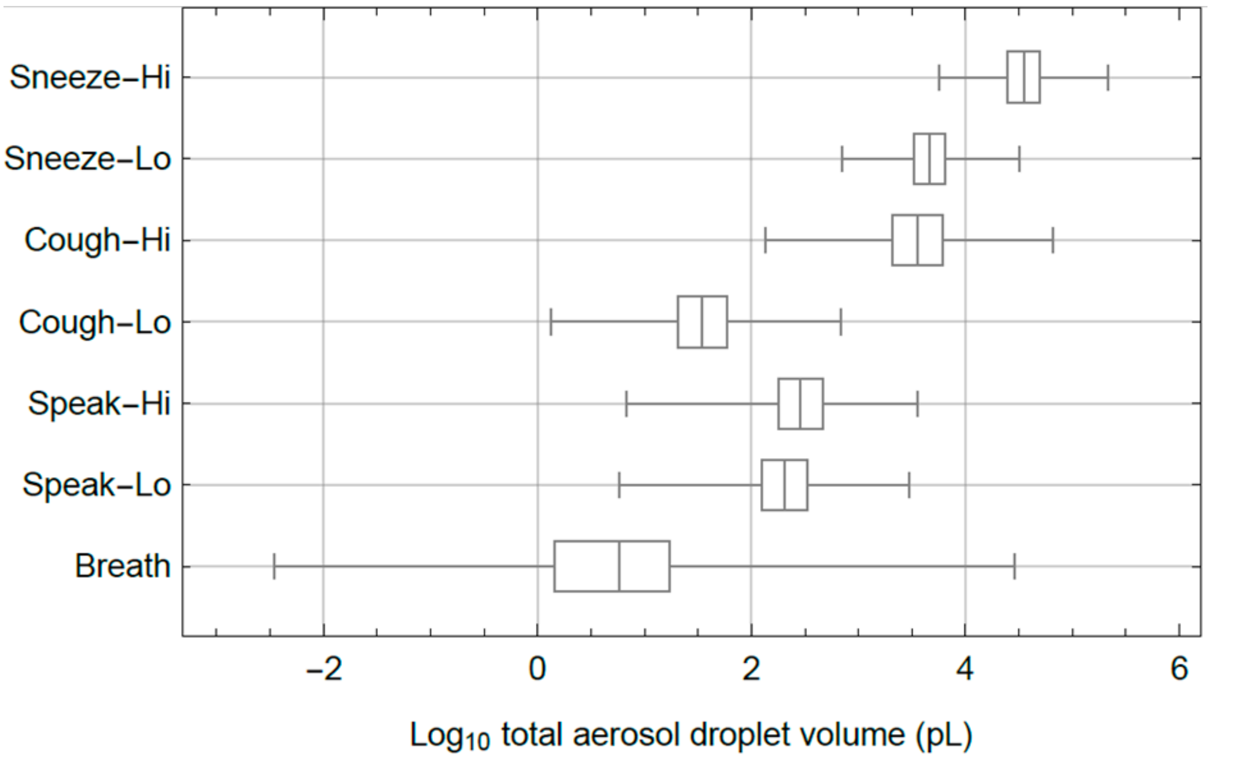

Figure 6: Log10 of total aerosol droplet volume produced during breathing, speaking, coughing and sneezing for different scenarios (high and low) (picolitre) (Schijven, et al., 2020)

Temperature and relative humidity of exhaled breath

Exhaled breath just after exhalation ranges in temperate from 31.4 - 35.4 degrees Celsius, and ranges in relative humidity from 41.9 - 91%, found a study of 31 subjects (Mansour, et al., 2020). The literature shows are range of values regarding the speed of exhaled breath during breathing, speaking, coughing, sneezing. For coughing, velocities are reported from 1.5 to 28.8 m/s (VanSciver, Miller, & Hertzberg, 2011), with reported averages of 11.2 m/s (Bourouiba, Dehandschoewercker, & Bush, 2014) and 11.7 m/s (Chao, et al., 2009). For sneezing, Tang et al (2013) report a sneeze velocity of 4.5 m/s. Bahl, de Silva, Chughtai, MacIntyre and Doolan (2020) report that most droplets in a sneeze travel at velocities of less than 5 m/s, but that a small fraction reaches > 10 m/s. Air velocity during speaking is somewhat lower, reported to be 3.9 m/s (Chao, 2009). For breathing, Tang et al. (2013) report 1.4 m/s for nasal breathing and 1.3 m/s for mouth breathing. Tang et al. also note that the exhalation plume for nasal breathing is directed downwards at 45-60 degrees away from the vertical, while mouth exhalation is directed horizontally.

SARS-CoV-2 concentrations in aerosol droplets

Analogous to Schijven et al. (2020), it is assumed that virus concentrations in aerosol droplets are the same as virus concentrations in nasopharyngeal swab samples, e.g. ranging from 10^2 to 10^{11} RNA copies / mL.

SARS-CoV-2 inactivation in aerosols

In general, viruses survive longer at lower temperatures, and inactivate more quickly at higher temperatures (Bertrand, et al., 2012). SARS-CoV-2 was found to be remarkably stable in laboratory-generated aerosols conditions; Fears et al. (2020) observed little decline in infectivity during 16 hours of aerosol suspension of SARS-CoV-2 (at 23±2 °C and 53±11% relative humidity). Van Doremalen et al (2020). observed that SARS-CoV-2 remained viable for hours in laboratory-generated aerosols, reduction in infectious virus particles from 3100 to 500 per litre air during 3 hours (at 21-23 degrees Celsius and 65% relative humidity). Based on half-life values reported by van Doremalen et al. (2020), an inactivation rate coefficient of 0.028 per minute can be derived.

According to Schuit et al (2020), at 20.1±0.3°C the mean inactivation rate of SARS-CoV-2 without simulated sunlight across all relative humidity levels (20%-70%) was 0.008±0.011 per minute (90% loss: 125 minutes).

4.3 Emission quantities of the virus

Observed SARS-CoV-2 concentrations in nasopharyngeal swabs (nose / throat swabs) spans a wide range, from 10^2 to 10^{11} RNA copies / mL (corresponding to a range of Ct values from 40 to 10.5) (Schijven, et al., 2020). The median is at 10^6 , and the 95 percentile at 10^8 copies / mL. See Table 3 for parameter of the normal distribution of the $\log_{10}$ transformed concentrations.

Van Kampen et al. (2020) found that only a viral load above 7 Log_{10} RNA copies/mL and absence of serum neutralizing antibodies were independently associated with isolation of infectious SARS-CoV-2 from their respiratory tract samples. The probability of isolating infectious virus was less than 5% when viral RNA load was below 6,63 Log_{10} RNA copies/mL. Van Kampen et al. (2020) also reported that detection of viral subgenomic RNA detection correlated poorly with shedding of infectious virus.

Lednicky et al. (2020) provided direct evidence that SARS-CoV-2 detected in aerosols can be intact virions. The intact virus fraction in air samples collected 2 to 4.8 m away from patients in a hospital room was on average 0.6 with a standard deviation of 0.17. They used VIVAS air samplers that collect virus particles without damaging them, thus conserving their viability. Preliminary RIVM data suggest that the fraction of intact virions in SARS-CoV-2 isolates can be up to 1/55=0.018, which will be used as a preliminary default. See Table 3.

Table 3: Viral modelling parameters, based on Schijven et al. (2020)

Model parameter	Symbol	Dimension	Default	Range	Distribution	Reference
Compartment						
Length	*l*	m				
Width	*w*	m				
Height	*h*	m				
volume	*v*	m				
Number of compartments		-				
Ventilation						
Ventilation rate	Q_v	l/s/p or m^3/h				
Fraction fresh air		-				
Filtration efficiency (HEPA)	*z*	-				
Relative humidity	*RH*	%				
Temperature	*T*	°C				
Virus properties						
Concentration in aerosol at onset of symptoms	*Ca*	/ml	10^8	10^2-10^{11}	Log_{10} of Ca, N[5.9;1.3]	Schijven et al. (2020)
Intact fraction	*f*	-	0.018	0.001-1		RIVM
Infectious fraction (exponential dose response)	*r*	-	0.054	0.001-0.1		Haas (2020), Schijven et al. (2020)
Inactivation rate coefficient (20.1±0.3°C and RH of 20-70%)	μ	/minute	0.008	±0.11		Schuit et al. (2020)
Contagious person						
Exhalation rate (tidal breathing)	Q_e	l/minute			N(Log_{10}(6.8); 0.050]	Schijven et al. (2020), Fabian et al. (2011)
Aerosol volumes breathing, speaking, coughing, sneezing	$V_{br,sp,co,sn}$			Monte Carlo data		Schijven et al. (2020)
numbers of expelled aerosol droplets during speaking	*Nsp*				LogNormal[5.1;0.67]	Duguid (1945), Asadi et al. (2019)
numbers of expelled aerosol droplets in one cough					LogNormal[11;0.8]	Duguid (1945), Lindsley et al. (2012)
numbers of expelled aerosol droplets in one sneeze					LogNormal[14;0.5]	Duguid (1945), Gerone et al. (1966)
Aerosol properties						
Entrainment coefficient, initial jet phase of a cough	α		0.24±0.02			Bourouiba et al. (2014)
Entrainment coefficient, second puff of a cough	α		0.132±0.06			Bourouiba et al. (2014)

Model parameter	Symbol	Dimension	Default	Range	Distribution	Reference
Entrainment coefficient, initial jet phase of a sneeze	*α*		0.13±0.02			Bourouiba et al. (2014)
Entrainment coefficient, second puff of a sneeze	*α*		0.055±0.01			Bourouiba et al. (2014)
Exposed persons						
Number	*Ni*	-				
Exposure time	*t*	h				
Inhalation rate (tidal breathing)	Q_i	l/minute			N(Log_{10}(6.8); 0.050]	Schijven et al. (2020), Fabian et al. (2011)

5 Transmission

Currently available evidence indicates that COVID-19 may be transmitted from person to person through several different routes.

In the scoping review published by La Rosa, Bonadonna, Lucentini, Kenmoe and Suffredini (2020), the human coronaviruses primary transmission mode is person-to-person contact through respiratory droplets generated by breathing, sneezing, coughing, etc., as well as contact (direct contact with an infected subject or indirect contact, trough hand-mediated transfer of the virus from contaminated fomites[12] to the mouth, nose, or eyes). Evidence is available for airborne transmission of various respiratory viral diseases, including SARS, MERS and influenza (Adhikari, et al., 2019; Kulkarni, et al., 2016; Weber & Stilianakis, 2008; Yu, et al., 2004; Zhang, et al., 2013). Airborne transmission has also been suggested to play at least some role in SARS-CoV-2 transmission (Anderson, Turnham, Griffin, & Clarke, 2020; Asadi, Bouvier, Wexler, & Ristenpart, 2020; Chia, et al., 2020; Li, et al., 2020; Morawska & Cao, 2020; Richard, et al., 2020; Shen, et al., 2020). Other studies contest this and suggest airborne transmission does not take place (Xu, et al., 2020) while e.g. Chen and co-workers (Chen, Zhang, Wei, Yen, & Li, 2020) suggest that even the majority of close-contact transmission is airborne instead of droplet transmission. Especially the ~5% of COVID-19-infected individuals that carry high viral loads of 10^8 RNA copies/mL or above in their nose / throat, may pose a significant risk for infecting others via the airborne route (Schijven, et al., 2020).

The available evidence suggests that COVID-19 is transmitted from person to person via several routes. The considered routes are listed below and they are shown graphically in Figure 8.

- *Direct droplet transmission: Transmission through direct exposure to larger respiratory droplets generated by breathing, speaking, coughing, sneezing, etc.*
- *Airborne transmission via smaller respiratory droplets and droplet nuclei (aerosols) that can stay airborne for a longer period of time.*
- *Contact transmission, e.g. by touching persons or fomites contaminated with virus.*

[12] A fomite is any inanimate object that, when contaminated with or exposed to infectious agents can transfer disease to a new host (Wikipedia, 2020)

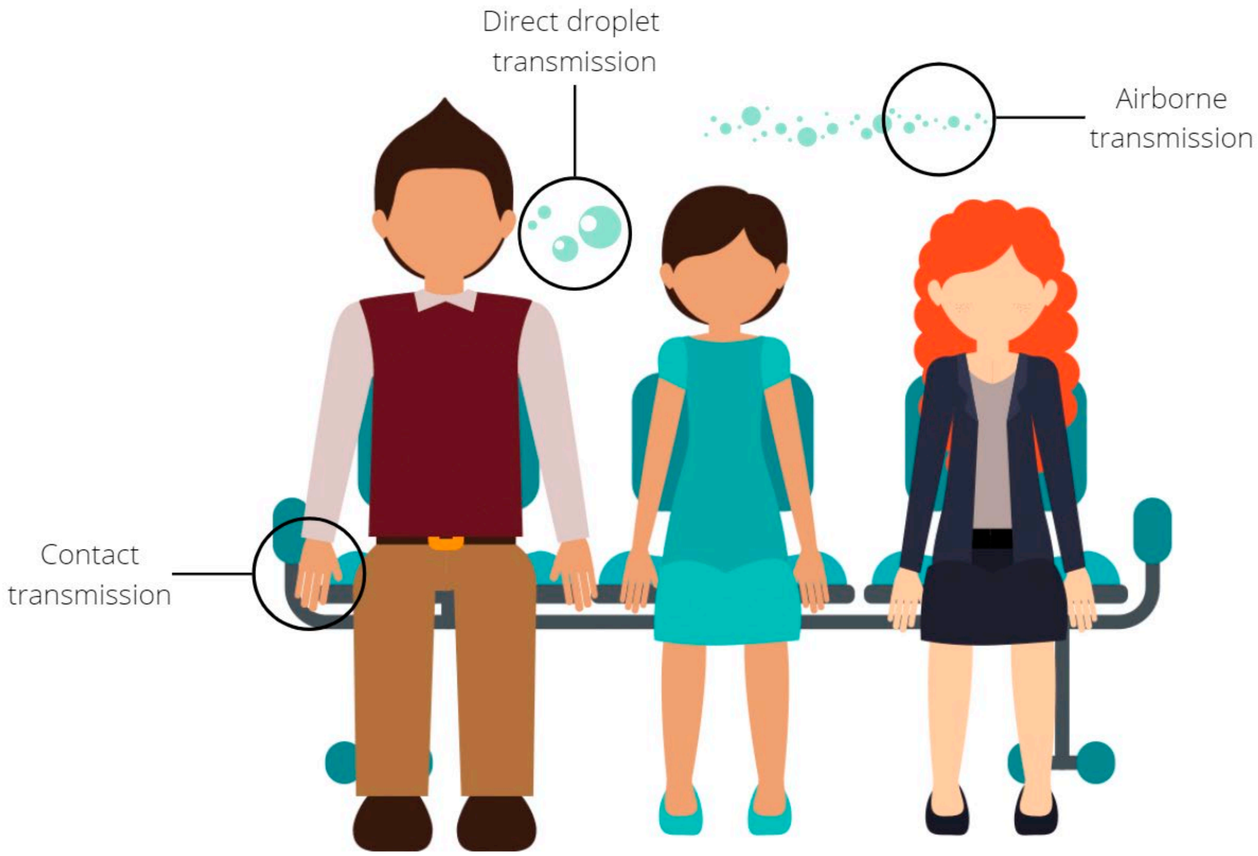

Figure 7: Graphic representation of transmission routes

The relative importance of each of these routes is not quantitatively known and difficult to investigate. Especially regarding the potential for airborne transmission, there is much discussion in the international scientific community.

5.1 Direct droplet transmission

SARS-CoV-2 can be spread by direct droplet transmission. Receivers can be exposed to the virus if such droplets end up in mucosa, for example in mouth, noise and/or eyes. This can occur directly as well as indirectly, such as through hand-mediated transfer. According to La Rosa et al. (2020), person-to-person contact through the respiratory droplets discussed here is the primary transmission mode for human coronaviruses.

The droplets that play a role in this transmission route are relatively large and heavy (initial diameter of more than 60 µm, based on Liu, Wei, Li, & Ooi, 2017). Due to their size and weight, they are unlikely to enter and travel through the ventilation system. The influence of gravity is larger than on smaller droplets and droplet nuclei that play a role in airborne transmission (further discussed in Section 5.2). This gravity effect is likely to limit the distance that the virus particles can spread, measured from the source emitter, to approximately 1.5 metres. The larger the droplets, the sooner they deposit.

The air flows associated to movement is unlikely to affect the path of larger droplets. In case a moving source emits larger droplets in various locations (e.g. when walking to or from the lavatory), the virus can of course be distributed through the cabin.

Even though the effect of the air flows caused by the ventilation system on larger droplets is likely small, the exact influence has to be determined using simulations and/or measurements. Gaspers, which are positioned relatively close to passengers, are of special interest.

5.2 Airborne transmission

The droplets and droplet nuclei that enable airborne transmissions are small and light-weight particles that can stay airborne for longer periods of time. Following Schijven et al. (2020), these are the droplets with an initial diameter of 60 μm, that, under relatively dry conditions, rapidly evaporate to a size three times smaller. The ventilation system used in aircraft, described in Section 3.3, is likely to have an important effect on the aerosol transmission of SARS-CoV-2 due to a number of system characteristics:

- Concentration of particles is lowered due to replacement with fresh outside air.
- Concentration of particles is lowered due to the HEPA-filter.
- Particles that are not captured by the ventilation system and/or HEPA-filter are distributed through the cabin.
- Virus particles might be affected by changes in temperature in the ventilation ducts and mixing manifold, as the pack exit temperature might differ from the average cabin temperature.

Furthermore, passenger movement and heat, might have a relevant effect on the air flow – and thereby on the distribution of the particles relevant for airborne transmission. Gravity, on the other hand, is estimated to have a small to negligible effect.

Although the qualitative effects of the ventilation system are assumed to be known, the magnitude of these effects (e.g. dilution, possible inactivation) has to be determined. This will be done based on generic literature and model simulations, such as aforementioned air supply requirements and standards, but will be supported with the help of measurements.

5.3 Contact transmission

Contact transmission consists of two elements: first, virus material emitted by the source emitter is deposited on a surface area, and second, it can be picked up by a recipient. As such, factors influencing direct droplet transmission also indirectly affect contact transmission. For both phases, the amount of interaction with their environment persons have influences the transmission likelihood in a straightforward manner.

6 Exposure

Haas (2020) reported on August 14, 2020 that Watanabe, Bartrand, Weir, Omura and Haas (2010) reviewed the literature for available data sets (human and animal) for development of dose-response models for various coronaviruses. Of these, there was only one human data set (with Coronavirus 229E) and this had the lowest median effective dose (most potent). The underlying data were from experimental work by Bradburne, Bynoe and Tyrrell (1967) in which human volunteers were dosed into their nostrils with different amounts of virus. The endpoint response was illness. Watanabe et al. (2010) found that the exponential dose response model provided a good fit to the data. The best fit value of k is 18.54, k is the dose-response parameter (interpreted as the inverse of the probability that one virus particle will survive and initiate the endpoint effect), indicating that each intact virus particle has a probability of 0.054 (dose response parameter r = 1/k in the exponential dose response model) of causing an adverse effect (Haas, 2020), such as illness.

In the sensitivity analysis of this study, the infectivity range (r) of 0.001 – 0.1 will be explored as a plausible range for human pathogens (Schijven, et al., 2016).

7 Measurements and simulations

The transmission of SARS-CoV-2 in aircraft cabins will be investigated by a combination of measurements and simulation. The next phase aims to combine the following relevant aspects regarding the transmission of SARS-CoV-2 during flights in a single study:

- The simulation of the large variation in SARS-CoV-2 virus characteristics
- The simulation of the air flow within the aircraft cabin under realistic aircraft conditions, based on flight measurements under operational conditions
- The simulation of the (non-uniform) spread of virus particles through the aircraft cabin, taking into account risk mitigation measurements as advised by ICAO and EASA
- Verification of the simulation with real, experimental flights

Each of the above aspects is potentially relevant for the transmission risk of the virus aerosols and droplets. Previous studies have addressed a number of these aspects (for example cabin air flow simulations based computational fluid dynamics, experimental studies in ground cabin mock-ups). To the best knowledge of the authors a single study with the combination of these aspects has never been published. The optimal combination of simulation and measurement will be determined in the next phase of this project.

7.1 Simulations

Accurate simulation of the air flow in an aircraft cabin is a complex and time-consuming task as a large variety of conditions might impact virus dispersion. Simulations will therefore first focus on a common cruise condition in the passenger cabin that is representative for a relatively large part of the flight. Similar conditions have also been studied in the literature, which allows for some verification with other studies, even if experimental results are not yet available. Based on this first condition, further scenarios can be simulated based on the simulation results. The decisions on further scenarios will be taken on the basis of the simulation results for this first condition, literature results, and (partial) sensitivity analysis. Potentially the simulation thus extends to other flight phases such as taxiing, and variations in occupation of seats.

For the air flow simulations and the particle dispersion simulations, different methods are used, as indicated in Table 4. The simulation of the transport of the droplets, mainly with the air flow, can be carried out after the simulation of the air flow. In this case the simulation is not coupled. However, the air flow is to some extent effected by the transport of the droplets and this can be simulated by iterating the two types of simulations, which increases the computational effort significantly. The significance of this effect relative to the effect of other parameters for the transmission risk of SARS-CoV-2 is unknown.

Table 4: Simulation methods for cabin air flow and spread of particles

Flow solver	Droplet modelling	Coupled	Computational effort	Remarks
RANS	Scalar transport	No	Low	Contaminant source term needed
RANS	Particles, fixed diameter	No	Medium	Particle diameter distribution can be used as input. Diameter fixed in time.
(U)RANS	Multiphase, carrier and discrete phase	Both	High (medium when not coupled)	Droplets can evaporate, coupled to carrier phase
LES/DES	Scalar transport and/or discrete particles	No	Very high	LES approach used to calculate initial cough and dispersion, scalar transport used for propagation contaminant into computational domain.

NLR has a simulation model suite which represents the ventilation system of an aircraft. In these simulation models the air-flows in the aircraft and cabin can be simulated (with a RANS flow solver) to represent the local climate in the passenger cabin. This model can also be extended for research on the spreading of viruses in the passenger cabin of the aircraft. Therefore, the exhalation, transport and inhalation of viruses in the cabin environment needs to be studied. In order to ensure the correct inputs and boundary conditions are used in the simulation model and to validate its results, measurements can be performed.

7.2 Measurements

In a single experimental campaign, a number of flight phases and conditions can be covered. Based on the available information from literature it is recommended to include both taxiing and cruise conditions. A real-life test flight yields the most realistic cabin environment in terms of cabin, air flows, pressure gradients, humidity and temperatures. This is of importance as these parameters likely affect the inactivation, behaviour and spreading of the virus particles and little verified data is readily available.

The measurements can be performed in two different ways. One option is the measurement of the boundary conditions in an aircraft: temperatures of the walls, ceilings, speed and quantities of flows injected into the cabin, configuration and dimensions of the aircraft interior, etc. This information can be used to do Computational Fluid Dynamic CFD calculations that include the physics of flow behaviour and particle movement in the cabin. The result of the calculations give insight in the concentrations of particles at multiple locations.

A more direct way of determining the concentrations is by measuring the spreading of real droplets and aerosols. Performing such a measurement is a challenge. For making it realistic with respect to the effects, the cabin needs to be filled with heat sources, like humans, as heat will change the movement of air inside the cabin. Therefore, the measurements need to be done with heated mannequins. The spreading of aerosols and droplets due to coughing, sneezing etc also needs to be simulated with a device, representative of a realistic source as described in the former chapters. After propagating through the cabin, the concentrations of the aerosols and droplets can be measured and give information on the spreading and the concentration of the aerosols.

7.3 Relevant aircraft types

To approach reality as close as possible, the simulations and measurements are of actual aircraft types, rather than generic models. The exact aircraft types will be based on their commonality in terms of number of passengers (expressed in number of seats) and 'passengers × distance flown' (expressed in seat kilometres) to and from Amsterdam Airport Schiphol in 2019.

Table 5 shows the number of seats and the number of available seat kilometres (ASK) per aircraft family. The number of seats is relevant, as it speaks to the likelihood of a passenger being on a plane, it being a plane of that particular type. The number of seat kilometres speaks to the likelihood of a passenger spending one hour in a plane, it being on a plane of that particular type. Given an increasing contamination risk over a prolonged period of time, the time-metric is deemed relevant.

Table 5: Number of seats and number of available seat kilometres (ASK) per aircraft family, based on operations to and from Amsterdam Airport Schiphol in 2019. The column 'Class' refers to the aircraft class (SA for single aisle; TA for twin aisle), discussed in Section 3.2

Aircraft family	Aircraft (sub)type[13]	Class	Seats (thousands)	Rank	ASK (millions)	Rank
Airbus A320 (excl. A320neo)	Airbus A318, A319, A320, A321	SA	16 075	2	15 009	5
Airbus A330	Airbus A330-200, -300	TA	6 204	5	36 491	2
Boeing 737 Next Generation	Boeing 737-600, -700, -800, -900	SA	**27 324**	**1**	36 156	3
Boeing 767	Boeing 767-300, -400	TA	1 933	7	11 054	6
Boeing 777	Boeing 777-200, -200LR, -300, -300ER	TA	7 248	4	**56 548**	**1**
Boeing 787	Boeing 787-8, -9, -10	TA	4 094	6	30 816	4
Embraer E-Jet	Embraer E170, E175, E190, E195	SA	11 470	3	7 617	7

The table shows that most seats were produced by aircraft of the Boeing 737 Next Generation family, a single aisle aircraft. Within that family, the Boeing 737-800 subtype produced most seats: more than 20 million, approximately 74% of the family total. The Airbus A320 family (especially: Airbus A320-subtype) and Embraer E-Jet family (especially: Embraer 190) produced the next most seats, respectively.

The highest number of available seat kilometres were produced by aircraft of the Boeing 777 family, a twin aisle aircraft. Within that family, the Boeing 777-300ER subtype produced most seat kilometres: 31 million, or about 54% of the family total. The Airbus A330 family (especially: Airbus A330-300), Boeing 737 (already identified as relevant type based on seats produced) and the Boeing 787 family (especially: Boeing 787-9) produced the next most seat kilometres, respectively.

Two additional remarks are in place:

- A large portion of the seat kilometres produced by the Airbus A330 is done so by KLM. If that airline were to retire its entire Airbus A330-fleet early (as currently speculated[14]), this would affect the number of seat

[13] The table groups aircraft (sub)types per aircraft family, because of product similarity (in e.g. cabin width, height and systems lay-out). For each family, the table shows which aircraft types are considered part of that family. The table is limited to aircraft families with more than 10 000 movements and sorted based on family name.
[14] https://luchtvaartnieuws.nl/nieuws/categorie/2/airlines/klm-praat-over-vervroegd-afscheid-a330s-maar-heeft-nog-geen-concreet-plan

kilometres produced by 16 million, such that approximately 20 million seat kilometres would remain. In that case, the Boeing 787 would overtake the Airbus A330 in the above ranking.

- As indicated in Section 3.3, the environmental control system of the Boeing 787 differs from most other aircraft, as the Boeing 787 does not use bleed air.

Following the selection of aircraft (among others, a factor of availability of aircraft for performing measurements), the more generic information in previous sections of this report (e.g. with respect to cabin dimensions and characteristics of the environmental control system) will have to be determined in order to correctly set up the simulations.

8 Conclusions

This report is the deliverable of the literature review phase of CORSICA. The report identified the most relevant parameters and their variance related to SARS-CoV-2 transmission in aircraft cabins. The parameters will be used as input for the upcoming measurement and simulation phase of the project.

The source emitter

Passengers or crew carrying SARS-CoV-2 can produce droplets ranging in size from <1 – 2000 µm during expiration events. In general, larger droplets produced by coughing that are >60 µm fall to the ground quickly within 1.5 meter, while smaller droplets can stay airborne. Size distributions and number of aerosols will be taken from recent RIVM-research, which distinguishes between breaking, speaking, coughing and sneezing.

Observed SARS-CoV-2 concentrations in nasopharyngeal swabs (nose / throat swabs) spans a wide range, from 10^2 to 10^{11} RNA copies / mL. The median is at 10^6 , and the 95 percentile at 10^8 copies / mL. Preliminary RIVM data suggest that the fraction of intact virions in SARS-CoV-2 isolates can be up to 1/55=0.018, which be used as a preliminary default.

Based on the effective use of mouth masks, an inhalation filtering efficiency of about 30%, and a reduction in droplet and aerosol emissions of about 60%, will be assumed. In case all persons wear a mask, this yields a total risk reduction of about 70%.

Transmission

Three transmission routes are deemed relevant: direct droplet transmissions (exposure to larger respiratory droplets), airborne transmission (via smaller respiratory droplets and aerosols) and contact transmission. The relative importance of each of these routes is not quantitatively known and difficult to investigate, although literature seems to note little cases of contact transmission.

The distribution of larger droplets is most likely influenced minimally by air flows inside the cabin. These flows are a result of the ventilation system (e.g. inflow and outflow), human factors (e.g. flow obstruction, breathing and movement) and gravity and acceleration effects. Smaller droplets and droplet nuclei (aerosols) can stay airborne for longer periods of time and can potentially enter into the ventilation system. Their concentration will be reduced due to the inflow of fresh air (mixed with recirculated air in an approximate 50:50-ratio) and effect of HEPA-filters. The aerosols not captured by the HEPA-filter will be distributed throughout the cabin by the ventilation system. Again, human factors (now also temperature gradients) are likely to influence distribution. Contact transmission is first – where the virus material is emitted and deposits on a surface – governed by the same processes as those influencing direct droplet and airborne transmission. The second phase, in which the virus is picked up by a recipient, is governed by human factors.

Virus inactivation will be modelled at a rate of 0.008±0.011 per minute, based on prior research in a slightly colder (minus 3.3°C) and more humid environment (plus 9%) than commonly observed in aircraft cabins during cruise flight.

Exposure

Little data is available on the response to SARS-CoV-2 exposure. The effect of a particular concentration of virus particles on a recipient is modelled by a dose-response relation. An infectivity range (r) of 0.001 – 0.1 will be explored as a plausible range for human pathogens.

Next steps: simulations and measurements

Simulations and measurements will be used to fill the remaining knowledge gaps and determine the SARS-CoV-2 transmission risk on board of aircraft. The optimal combination of simulation and measurement will be determined in the next phase of this project, addressing direct droplet transmission and airborne transmission.

For the simulation it is recommended to study a common cruise condition in the passenger cabin that is representative for a relatively large part of the flight first. Similar conditions have also been studied in the literature, which allows for some verification with other studies, even if experimental results are not yet available. Based on this first condition, further scenarios can be simulated based on the simulation results. The decisions on further scenarios will be taken on the basis of the simulation results for this first condition, literature results, and (partial) sensitivity analysis. Potentially the simulation thus extends to other flight phases such as taxiing, and variations in occupation of seats.

A single experimental campaign can cover a number of flight phases and conditions. Based on the available information from literature it is recommended to include both taxiing and cruise conditions. A real-life test flight yields the most realistic cabin environment in terms of cabin, air flows, pressure gradients, humidity and temperatures. This is of importance as these parameters likely affect the inactivation, behaviour and spreading of the virus particles and little verified data is readily available. Measurements can focus on validating environmental conditions used as input for simulations or directly measure virus dispersal simulated with a device that simulates particle emission from a passenger.

Aircraft movements at Amsterdam Airport Schiphol in 2019 were used to determine the aircraft types occurring most (in terms of production of seats and seat-kilometres). These would be relevant aircraft for performing the simulation and measurements. The Boeing 737(-800) and Airbus A320 were determined to be relevant single aisle aircraft, the Boeing 777(-300ER), Airbus A330(-300) and Boeing 787(-9) were determined to be relevant twin aisle aircraft.

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