MAYOR OF LONDON

TRANSPORT FOR LONDON
EVERY JOURNEY MATTERS

Agenda

Meeting: Safety, Sustainability and Human Resources Panel

Date: Wednesday 4 November 2020

Time: 10.00am

Place: Teams Virtual Meeting

Background Information

6 Update on Response to the findings of the UCL research into Covid-19 Bus Driver Fatalities (Pages 1 - 50)

UCL Report on Scientific advice to TfL on bus driver assault screen modifications due to the Covid-19 pandemic

Report on Scientific advice to TfL on bus driver assault screen modifications due to the Covid-19 pandemic

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Executive Summary

In April 2020 Transport for London (TfL) commissioned the UCL Department of Civil, Environmental and Geomatic Engineering (CEGE) to explore measures to mitigate the occupational risk posed to London bus drivers from the COVID-19 pandemic, following the tragic deaths of a number of drivers among bus operators within London. A separate study undertaken by UCL's Institute of Health Equality has examined more comprehensively a number of other risk factors affecting bus drivers, including beyond their occupational risk. Phase one of that study was published on the 27th July 2020 and has determined that "there is evidence that among bus drivers those aged 65 and over, those from BAME backgrounds and those with pre-existing hypertension are at a higher risk of COVID-19 mortality and this should be taken into accounts in efforts by TfL and bus companies to reduce risks"[1]. TfL asked UCL CEGE to explore the nature of this occupational risk in relation to the interaction between passengers and the bus driver, and the effects arising as a result of the design of the bus itself, in particular the assault screen. The assault screen is a pre-existing transparent polycarbonate fixture designed to resist physical attacks, such as stabbings, while allowing the driver to have both a clear view through the screen, access the electronic ticket machine and provide receipts when required, and the ability to be able to hear and speak to passengers as the need arises. It was not originally designed to keep the driver completely isolated from the passengers.

1. This work was commissioned by TfL because consideration of driver's protection was deemed necessary, due to the potential for prolonged exposure to airborne viruses and pathogens such as, potentially, SARS-CoV-2. We do not yet know precisely how much SARS-CoV-2 is present in aerosols or what the precise risk of infection is.
2. Droplets will settle on surfaces around the passenger as is well known. However, in additional to droplets, aerosols are generated by human expiratory activities and these remain suspended in air and can be transported around a bus via local airflows. These can be simulated and predicted using Computational Fluid Dynamics.
3. A set of detailed models was created of the front part of a typical London bus, including both front and central doors, the driver's cabin and a detailed dynamic model of the bus driver, and then detailed simulations were carried out. These calculated the motion of aerosols emanating from a passenger who is coughing and breathing in a number of positions relative to the driver's cabin under a variety of design and operational scenarios in order to identify appropriate interventions. A typical screen and bus design were chosen for the simulations, that addressed all the relevant design issues - gaps, door and window operations - as a representative case for all buses.
4. The original (pre-COVID) designs of polycarbonate dividers or screens were only marginally protective against aerosols and were not sufficient on their own to protect against airborne transmission of SARS-CoV-2.

[1] *Goldblatt P and Morrison J (2020) Initial assessment of London bus driver mortality from COVID-19; report prepared for TfL by UCL Institute of Health Equity, http://www.instituteofhealthequity.org/resources-reports/london-bus-drivers-review*

5. A set of recommendations has been made with the aim of reducing this risk to London drivers in particular as much as is practically possible, further to interventions already initiated by TfL. A brief summary of these follows:
   a) Modifications to the assault screens such that the speech holes are covered and the gaps around them to be no more than 5 mm wide
   b) Avoid recirculation of air between the saloon and the driver's cab, so that the air in the cab is kept separate to the passenger saloon in terms of the air supply.
   c) Modifying the ventilation system so that the driver has their own system that is separate from the passenger saloon and draws air from an outside source of fresh air. In order to ensure safe CO_2 levels inside the cab, the cab ventilation system must provide high standards of indoor air quality.
   d) Opening the window in the driver's cab until these ventilation systems are adapted.
   e) Return to front door boarding and operate boarding procedures such that both front and middle door are opened to increase ventilation on the bus.
6. Buses in large cities are a unique indoor environment that is confined and often crowded at rush hour or in tourist season and, if poorly ventilated there is potential for airborne transmission of infectious diseases which may pose a risk to drivers due to their prolonged exposure times.
7. Further work is required to determine if there may be a risk to passengers too, if they are on board for long journeys. It is impossible at present to estimate how long is "a long journey", but assessments in the literature consider that exposure to an infected person without a face covering of over 15 minutes may increase risk. It is important to note that most passengers will not be infected at all. Current guidelines on social/physical distancing ensure that overall passenger numbers are low so that the risk of being in the presence of an infectious passenger is greatly reduced and the risk of infection even if such a passenger is present is also greatly reduced. This situation may change in the future, and the problem of asymptomatic carriers is concerning, and it is thus recommended that passive measures to reduce airborne transmission are adopted. At the moment the most practical and simple recommendation is that windows are left open in the passenger saloon, though this may prove to be challenging for passengers in the winter.
8. Quantifying exposure risks considering both drivers and passengers wearing face masks was beyond the scope of this study and this is recommended for further study in order to better understand their effectiveness in reducing risk to passengers and to drivers in other industries that do not have built-in protection screens. However, it is clear, given all the new understanding gained in the scientific community around airborne transmission in the past few months, that it would be best to continue to require all passengers to wear face masks.
9. Regardless of any mechanical or physical interventions to reduce risk, it is recommended that in the medium-term, targets for Indoor Air Quality (IAQ) standards on public transport are developed and adopted. This, due to the high number of daily passengers, some of whom have long journey durations (>1hr if commuting from zones 4 and beyond) and the prevalence of infectious diseases such as influenza and the common cold in the population every winter season, which carry large economic costs and also cost lives. The emergence of highly infectious and more dangerous diseases in the UK and around the world in the past two decades, such as SARS-CoV-2, SARS, H1N1 (swine flu) or MERS, all indicate that it is very timely to invest efforts towards maintaining healthy and safe indoor air on public transport.

Proposals for future research:

The results of this work have yielded a number of questions about the operation of buses in a COVID world. First, this work was very specific to the situation pertaining to the driver and the cabin in which they work. Subsequent projects are underway to examine the situation in the rest of the bus – the passenger saloons on both upper and lower decks.

In the next stage of this work the passenger saloon area will be considered more in depth under the VIRAL project (Reducing Risk of COVID-19 Virus Transmission on London's Public Transport: https://bit.ly/uclviral). Investigations into potential virus transfer risk and general air quality will be completed and recommendations provided to TfL on the findings and opportunities for improvement on double door single deck, double door double deck and single door single deck vehicles. This will be done via air quality measurements and modelling as well as CFD modelling on the passenger saloon area, including the effect of the HVAC systems and door openings. Physical measurements of air flows and conditions will be performed to consider the personal exposure of passengers during a journey and Microbiological testing will provide a microbiological profile using air and surface sampling. Different seasons and operational scenarios (e.g. peak / off peak) will be considered. It is expected that early results may be available late 2020, with project completion in late 2021.

Secondly, the isolating of the driver's cabin from the main passenger saloon within the bus has implications for air quality within the driver's cabin, especially in periods of inclement weather, when the likelihood will be that the driver would want to close their window. Therefore, these implications need to be explored urgently, so that air quality is assured to be appropriate, not least to ensure that drowsiness due to a build-up of Carbon Dioxide in the cabin is avoided. At present this can be mitigated by opening the driver's window as often as possible. Research is now underway to assess the viability of having CO_2 detectors installed and connected to the air circulation system in the cabin in order to maintain and control the cabin air quality.

Thirdly, the finding that ventilation is key to reducing the risk of infection transmission means that we should investigate the current movement of air within and through buses, and consider whether the current situation, which predominantly relies on natural ventilation within the vehicle (i.e. using ingress of external air via the windows and doors) is sufficient, and if not how some form of mechanical system should be specified to ensure that the ventilation rates are sufficient. This potentially has a profound implication for the transition to fully electric buses, as the energy requirement for such a system is at odds with the capacity to provide energy for this and to drive the bus. Therefore, an essential piece of work is required to define the HVAC requirements together with the energy implications and potential solutions.

Fourthly, it is clear that there is still a lack of knowledge about the transmissibility of the virus in enclosed situations, such as buses and other interior public spaces, and the actual safe physical distancing that should be recommended. Therefore, there is a need for research to be undertaken in an environment that can realistically represent these environments, with a range of temperature, humidity and air handling specifications, with appropriate analysis of how suitable (benign) virus surrogates are spread around the facility in a variety of controlled operational scenarios and occupancy. Such a research facility does not yet exist in the UK, and a strong recommendation from this research is that it is an urgent requirement.

Finally, there is a need to establish whether the present financial models, based on highly intense operations in the peak hours, are actually sustainable in a situation where the number of peak hour passengers on a bus may need to be reduced, either because of a reduction in passengers due to changes in working patterns, or specifically to reduce the maximum number of passengers on a bus in order to improve air circulation within the passenger saloons.

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Introduction

In April 2020 Transport for London (TfL) commissioned the UCL Department of Civil, Environmental and Geomatic Engineering (CEGE) to explore measures to mitigate the occupational risk posed to London bus drivers from the COVID-19 pandemic, following the tragic deaths of a number of drivers among bus operators within London. A separate study undertaken by UCL's Institute of Health Equality has examined more comprehensively a number of other risk factors affecting bus drivers, including beyond their occupational risk. Phase one of that study was published on the 27th July 2020 and has determined that "there is evidence that among bus drivers those aged 65 and over, those from BAME backgrounds and those with pre-existing hypertension are at a higher risk of COVID-19 mortality and this should be taken into accounts in efforts by TfL and bus companies to reduce risks"[2]. TfL asked UCL CEGE to explore the nature of this occupational risk in relation to the interaction between passengers and the bus driver, and the effects arising as a result of the design of the bus itself, in particular the assault screen. The assault screen is a pre-existing transparent polycarbonate fixture designed to resist physical attacks, such as stabbings, while allowing the driver to have both a clear view through the screen, access the electronic ticket machine and provide receipts when required, and the ability to be able to hear and speak to passengers as the need arises. It was not originally designed to keep the driver completely isolated from the passengers.

Contextual Background

Two possible transmission routes on a bus were immediately apparent in relation to SARS-COV-2 on a bus. These were the transmission of the virus via surfaces and the transmission via air.

Whereas a passenger is likely to be on a bus for an average of 14 minutes (in 2019/20, TfL), having potentially very short exposure time to other passengers and therefore, it is assumed, limited risk of infection by airborne transmission, the driver is on a shift of a few hours, with a typical journey length of around an hour, a layover of a few minutes and a return to the starting point before a significant break, with time off the bus.

Most of London's buses have a 2-door system – with passengers entering by the front door and leaving by the centre door. A few buses only have a single door, so passengers must pass by the driver both as they enter the bus and also as they leave the vehicle. In normal operation, on 2-door buses all passengers pass by the driver's cabin as they enter the bus, in order to 'touch in' their Oyster, pass or bank card to pay for the journey, and leave by the centre door.

The concern brought to us initially, in April 2020, was mainly regarding the possibility that passengers would cough or sneeze as they were passing by the driver producing large droplets that might get through the assault screen (through the speech holes or around it through the gaps). This concern was based on the accepted methods of transmission and the best available scientific advice at that time. Our team was concerned that as well as large droplets, there may be large numbers of tiny droplets (aerosols) in the air, particularly at peak time when passenger numbers could be as high as 80-90 on a double decker bus. We were concerned that as changes had been made over the years to window sizes, making them smaller to improve passenger safety, there was a risk that ventilation rates on the bus are low. This is something that would not be risky in normal times but in the situation where a new virus was present, that was similar to the virus that caused the SARS epidemic of 2002-2004, we advised caution against any possibility that the disease is "airborne" and that the drivers may become infected by asymptomatic passengers who do not even know

[2] *Goldblatt P and Morrison J (2020) Initial assessment of London bus driver mortality from COVID-19; report prepared for TfL by UCL Institute of Health Equity, http://www.instituteofhealthequity.org/resources-reports/london-bus-drivers-review*

they are ill. Protecting only against larger droplets and advising on cleaning strategies did not seem enough to reduce the risk to the drivers substantially.

The UCL team therefore ran a set of simulations of air flow to test different protective measures around the assault screens and see what was needed to lower the number of tiny droplets entering the driver's cab to as close as possible to zero, in a fast and robust way that could be implemented quickly across the network, while still improving ventilation and fresh air for the driver. We had assumed that face coverings would not be used (in fact they were strictly not recommended at the time this project began and even now we are aware that it cannot be guaranteed that people will always cover their nose and mouth whilst on a bus).

This report is structured as follows. Section 3 explains some scientific background relating to the SARS-CoV-2 pandemic. Section 4 considers bus operations and how these are affected by the SARS-CoV-2 pandemic. Section 5 summarises the main results of modelling of air circulation in and around the driver's cabin under a number of different operating scenarios (the full description and results of this research are given in Appendix A). Section 6 discusses recommendations following from this research in relation to the driver's cabin. Section 7 provides a summary and discusses further research that is required in order to resolve the challenges for the passenger saloons in the short and longer term.

Scientific background

The scientific rationale underpinning the recommendations made by the team at UCL was first summarised in a report entitled "Clean indoor air in the COVID-19 pandemic: the case for improving ventilation standards" (Appendix B), which was submitted to Sage Environmental Modelling Group on the 18th of May and presented as an annex to their main evidence paper to Sage. The main points raised in that paper are summarised below, having been updated with newly published scientific evidence that has come to our attention since that date, and acknowledging some Sage EMG reports that have since then become available online[3][4] [5] [6].

3.1 Routes of Transmission and Infection

In the early days of the pandemic it was widely believed that the primary route of infection in COVID-19 is through contact with contaminated surfaces, and exposure to larger droplets produced by coughs and sneezes. However, some later research started to point to the possibility of smaller aerosols being involved in transmission. A rapid expert consultation response to the US National Academies of Sciences, Engineering and Medicine was published on April 1st, 2020. The authors concluded that "While the current SARS-CoV-2 specific research is limited, the results of available studies are consistent with aerosolization of virus from normal breathing"[7]. They also noted that for any respiratory virus it is impossible to state precisely what proportion of infections occur due to air droplet, aerosol or fomite transmission. There is now a growing body of evidence and growing consensus that there can be additional transmission through very small aerosols suspended in air, especially in closed indoor environments. This has not yet been conclusively proven by direct experimentation, but the virus has been shown to remain viable in aerosols in the

[3] *Evidence of environmental dispersion for different mechanisms, and the risks and potential mitigations/measures of control within different environments from what we know about COVID19: A brief evidence summary for SAGE,* 14 Apr 2020

[4] *Environmental Influence on Transmission,* 2 May 2020, SAGE Environmental Modelling Group

[5] *Transmission and Control of SARS-CoV-2 on Public Transport,* 18 May 2020, SAGE Environmental Modelling Group

[6] *Transmission of SARS-CoV-2 and Mitigating Measures*, 4 June 2020, SAGE Environmental Modelling Group

[7] Fineberg, H., V., et al., *Rapid Expert Consultation on the Possibility of Bioaerosol Spread of SARS-CoV-2 for the COVID-19 Pandemic (April 1, 2020)* (2020). National Academies Press. doi: 10.17226/25769.

air, first for at least 3 hours[8], and subsequently, for at least 16 hours[9], with both studies concluding that transmission through the air is highly plausible. It is known that physiological processes such as breathing, talking, and coughing do produce large numbers of very small aerosols as well as larger droplets, in varying concentrations[10]. There are different definitions around the scientific community regarding aerosol and droplet sizes which create controversy around the use of the word "airborne". Research has shown conclusively that all those particles that are smaller than 50-100 microns, will be airborne for long enough to travel several metres and not, as first believed in the medical community, only those smaller than 5-10 microns[11]. Morawska, a prominent aerosol scientist, had been calling for the medical establishment to accept that the virus exhibits airborne transmission since April[12]. A report released in May[13], investigating infection and transmission of this virus between ferrets, concluded the possibility of airborne transmission to the ferrets that had not had direct contact with the infected individuals. Morawska and a group of 239 scientists have since signed a letter to the WHO calling on them to revisit their assessment of airborne transmission[14]. On the basis of the best evidence available to us and numerous discussions and conference communications from leading experts in fluid mechanics around the world, we consider that for close contact transmission indoors, short-range airborne route may *dominate* exposure and can be significantly more important than droplet transmission, especially when there is poor indoor ventilation and large numbers of people.

Viral load in asymptomatic carriers has been reported to be as high as in individuals with symptoms[15] and asymptomatic individuals have been shown to be a route for infection. Experimental research on speech droplets concludes that there is a high probability that normal speaking causes airborne virus transmission in confined environments[16]. Thus, asymptomatic carriers may be unwittingly exposing essential workers such as bus, coach and taxi drivers, and people working in retail, leisure and other service occupations to SARS-CoV-2. Male bus and coach drivers under the age of 65 have been identified[2] as having had high rates of death, 68 per 100,000, which is higher than expected based on the perceived risk of these jobs: the ONS has estimated that their potential exposure to COVID-19 as ranking 43 out of 359 jobs in their database, on the basis of closeness and exposure[17]. The ONS did not seem to consider airborne transmission in its analysis of exposure and it is this aspect that our project has sought to address.

Since 15th June, face coverings were made mandatory for customers / passengers on public transport, a move that was very much welcomed by our team. The use of face coverings is thought to significantly reduce the risk that these asymptomatic carriers would emit virus into the air. However, it may not be possible to guarantee that all bus passengers will be wearing them correctly at all times, or that all face coverings are of sufficiently high quality. There have been many reports of people refusing to wear face coverings for the duration of their journey and many people are also exempt from wearing face coverings due to disabilities or otherwise. All this suggests that additional

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[8] van Doremalen, N. *et al.* (2020) 'Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1', *The New England journal of medicine*. NLM (Medline), pp. 1564–1567. doi: 10.1056/NEJMc2004973.

[9] Fears SC, Klimstra WB, Duprex P, Hartman A, Weaver SC, Plante KS, et al. *Persistence of severe acute respiratory syndrome coronavirus 2 in aerosol suspensions*. Emerg Infect Dis. 2020 Sep, https://doi.org/10.3201/eid2609.201806

[10] Morawska, L. *et al.* (2009) 'Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities', *Journal of Aerosol Science*. Elsevier Ltd, 40(3), pp. 256–269. doi: 10.1016/j.jaerosci.2008.11.002.

[11] Wenzhao Chen, Nan Zhang, Jianjian Wei, Hui-Ling Yen, Yuguo Li, (2020) *Short-range airborne route dominates exposure of respiratory infection during close contact*, Building and Environment, Volume 176, 2020, https://doi.org/10.1016/j.buildenv.2020.106859

[12] Morawska L, Cao J. *Airborne transmission of SARS-CoV-2: The world should face the reality*. Environ Int. 2020;139:105730. doi:10.1016/j.envint.2020.105730

[13] Kim, Y.I., et. Al., *Infection and Rapid Transmission of SARS-CoV-2 in Ferrets*, Cell Host & Microbe, **27**(5*)*, p704-709, 5 2020 https://doi.org/10.1016/j.chom.2020.03.023

[14] Lidia Morawska, Donald K Milton, *It is Time to Address Airborne Transmission of COVID-19,* Clinical Infectious Diseases, ciaa939, https://doi.org/10.1093/cid/ciaa939

[15] Rothe et al 2020 - https://www.nejm.org/doi/full/10.1056/NEJMc2001468

[16] Stadnytskyi, V. et al. (2020) 'The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission', *Proceedings of the National Academy of Sciences of the United States of America*. NLM (Medline), 117(22), pp. 11875–11877. doi: 10.1073/pnas.2006874117.

[17] https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/causesofdeath/bulletins/coronaviruscovid19relateddeathsbyoccupationenglandandwales/deathsregistereduptoandincluding20april2020#men-and-coronavirus-related-deaths-by-occupation (accessed 17/5/20)

protection measures for bus drivers are still warranted despite the new requirement to wear face coverings on public transport.

3.2 Virus infectious dose and other airborne diseases

The amount of virus exposure needed to cause an infection - the infectious dose - for SARS-CoV-2 is still unknown at present. There have been a large number of studies into other respiratory diseases such as influenza to determine their infectious dose and the routes of transmission[18], with aerosols considered a viable route for transmission in some of them. The infectious dose of SARS-CoV-2 is not likely to be known for a long time as it would not be feasible to deliberately infect volunteers with the virus to determine the infectious dose (as determined for other diseases), and only some limited studies have been carried out in animals so far[13 19]. It can only be determined a-priori, when a known outbreak has been investigated fully.

Thus, previous pandemics could be considered in assessing the potential for infection and subsequent risk to health with SARS-CoV-2. The initial dose of virus was found to be a factor in the high mortality of the second and third waves of the 1918-1919 Spanish flu epidemic[20]. There is some evidence that the initial infectious dose may also worsen the severity of the illness with COVID-19[21]. Reducing the initial dose, where possible, may lead to better outcomes following an infection and perhaps this may prevent some deaths in the population and especially in those drivers who are already more vulnerable to the virus due to health factors or background.

3.3 Outbreaks in crowded indoor environments

Influenza is believed to be airborne and to be very easily transmissible by breathing the air in crowded places; a recent study detected influenza virus directly in air samples in a primary school and quantified the virus, concluding that the virus was present in doses high enough to cause infection[22]. During the SARS epidemic of 2002-2004, possible airborne transmission of SARS-CoV-1 was suspected in some super-spreading events such as in a hospital in Canada and the Amoy Gardens in Hong Kong.

Anecdotal evidence is constantly emerging of high rates of attack for SARS-CoV-2 originating from asymptomatic infected individuals in crowded indoor environments, coupled with poor ventilation or air conditioning systems set to recirculation mode. Super-spreading events have also been widely publicised by the media. A few cases that have been investigated in detail include: an analysis of two outbreaks in Zhejiang, China, one linked to infected people travelling on two coaches to a temple and the other at a training workshop in a conference room[23]; a restaurant in Guangzhou[24], which has also been modelled in detail in relation to other occupants and passengers and linked their locations and the airflows in the room to infections[25]. A well-publicised outbreak occurred in Skaget Valley, Washington, USA when one infectious person unknowingly attended the SVC chorale rehearsal, resulting in confirmed or strongly suspected infection of 53 members of the SVC among 61 in attendance. It was found that this event

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[18] Yezli, S., Otter, J.A. *Minimum Infective Dose of the Major Human Respiratory and Enteric Viruses Transmitted Through Food and the Environment*. Food Environ Virol 3, 1–30 (2011). https://doi.org/10.1007/s12560-011-9056-7

[19] Imai, M., et al *Syrian hamsters as a small animal model for SARS-CoV-2 infection and countermeasure development,* Proceedings of the National Academy of Sciences Jul 2020, 117 (28) 16587-16595; DOI: 10.1073/pnas.2009799117

[20] Paulo, A. C. *et al.* (2010) 'Influenza Infectious Dose May Explain the High Mortality of the Second and Third Wave of 1918–1919 Influenza Pandemic', *PLoS ONE*. Edited by R. Belshaw. Public Library of Science, 5(7), p. e11655. doi: 10.1371/journal.pone.0011655.

[21] Carl Heneghan, Jon Brassey, Tom Jefferson, Oxford COVID-19 Evidence Service Team, Centre for Evidence-Based Medicine https://www.cebm.net/covid-19/sars-cov-2-viral-load-and-the-severity-of-covid-19/ (accessed 17/5/20)

[22] Coleman, K. K. and Sigler, W. V. (2020) 'Airborne Influenza A Virus Exposure in an Elementary School', *Scientific Reports*. Nature Research, 10(1), pp. 1–7. doi: 10.1038/s41598-020-58588-1

[23] Shen, Y. (2020) et al 'Airborne transmission of COVID-19: epidemiologic evidence from two outbreak investigations' (preprint. https://www.researchgate.net/publication/340418430_Airborne_transmission_of_COVID-19_epidemiologic_evidence_from_two_outbreak_investigations?channel=doi&linkId=5e87b59ba6fdcca789f10d66&showFulltext=true) (accessed 17/5/20)

[24] Lu, J. *et al.* (2020) 'COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020', *Emerging Infectious Diseases*. NLM (Medline), 26(7). doi: 10.3201/eid2607.200764.

[25] Li, Y. *et al.* (2020) 'Evidence for probable aerosol transmission of SARS-CoV-2 in a poorly ventilated restaurant', *medRxiv*. Cold Spring Harbor Laboratory Press, p. 2020.04.16.20067728. doi: 10.1101/2020.04.16.20067728.

indicates transmission by the aerosol route was likely; and that it was difficult to explain many of the cases by either fomite or ballistic droplet transmission alone. Recommendations were made to avoid recirculation of HVAC systems during the pandemic as this could lead to the spread of airborne infection[26].

An analysis carried out in China[27], of case reports from 320 municipalities from a one-month period in January-February 2020 identified 318 SARS-CoV-2 outbreaks that had given rise to more than three infections. These were analysed and categorised, and all but one infection occurred indoors, including on public transport. It is notable that the study refers to the period in China when over 500m undertake long-haul travel home in very congested conditions, and thus does not represent the conditions pertinent to short duration passenger travel on buses in London, so are considered no further here. Similarly, a comparison of clusters of infection in northeast China found that public transport contributed to spread the infection over long distances by transporting infected individuals, but did not find much evidence of infections occurring within vehicles[28].

3.4 The role of ventilation systems

The crucial role of ventilation gained special recognition during the SARS epidemic of 2003, when an outbreak at The Prince of Wales Hospital in Hong Kong was linked to poor performance of the ventilation system[29]. The SARS epidemic, along with MERS, H1N1 influenza, and the possibility of bio-terrorism all have been identified as potentially serious threats in public spaces. Investigations of indoor ventilation systems identified them as effective strategies to lower infections for SARS and influenza in a wide variety of settings outside hospitals[30]. To date, high rates of ventilation to flush out contamination with fresh air remain the only identified mitigation measure, however there is some discussion amongst aerosol and ventilation academics on the efficacy of engineering controls such as filters and portable air cleaners for reducing infection risk.

In one noteworthy case, SARS was found to be transmitted on an aircraft, in which more than 90% of infections occurred in passengers seated more than 1 m away from the patient, and two infections occurred up to 7 rows away. After one flight carrying a symptomatic person and 119 other persons, laboratory-confirmed SARS developed in 16 persons, 2 others were given diagnoses of probable SARS, and 4 were reported to have SARS but could not be interviewed. Among the 18 interviewed persons with illness, the mean time from the flight to the onset of symptoms was four days (range, two to eight), and there were no recognized exposures to patients with SARS before or after the flight. Illness in passengers was related to the physical proximity to the index patient, with illness reported in 8 of the 23 persons who were seated in the three rows in front of the index patient, as compared with 10 of the 88 persons who were seated elsewhere. Airborne small aerosol particles rather than large droplets were identified as the likely explanation[31], and it was not believed to have been actively spread by the ventilation system. In contrast, another flight carrying four symptomatic persons resulted in transmission to at most one other person. Aircraft HVAC systems are usually specified to a high standard and employ personalised passenger systems, yet the long journey time means that airborne transmission may still have been possible; the ventilation system itself or how it was operated on that aircraft were not investigated. It is uncertain to what extent transmission on buses occurs, especially given there is not yet enough evidence of how transmission may occur amongst passengers. Potential methods of transmission are

[26] Marr, L. C. *et al.* (no date) 'Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event'. Available at: https://scholar.colorado.edu/concern/articles/n583xw008 (Accessed: 8 October 2020. Accepted by *Indoor Air, 15 September 2020)*.
[27] Hua Qian, Te Miao, Li LIU, Xiaohong Zheng, Danting Luo, Yuguo Li, *Indoor transmission of SARS-CoV-2,* medRxiv 2020.04.04.20053058; doi: https://doi.org/10.1101/2020.04.04.20053058 (pre-print)
[28] Zhao, P., Zhang, N. and Li, Y. (2020) 'A comparison of infection venues of COVID-19 case clusters in northeast China', *International Journal of Environmental Research and Public Health*. MDPI AG, 17(11), pp. 1–14. doi: 10.3390/ijerph17113955.
[29] Li, Y. et al. (2005) R*ole of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong*, Indoor Air. John Wiley & Sons, Ltd, 15(2), pp. 83–95. https://doi.org/10.1111/j.1600-0668.2004.00317.x
[30] Qian H, Zheng X. (2018) 'Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings.' *J Thorac Dis*. 2018;10(Suppl 19):S2295 - S2304. doi: 10.21037/jtd.2018.01.24
[31] Olsen, S. J. *et al.* (2003) 'Transmission of the Severe Acute Respiratory Syndrome on Aircraft', *New England Journal of Medicine*, 349(25), pp. 2416–2422. doi: 10.1056/NEJMoa031349

being researched in phase two of our study, which is being carried out under the VIRAL project (Reducing Risk of COVID-19 Virus Transmission on London's Public Transport: https://bit.ly/uclviral) .

3.5 Risk of Infection

Due to the lack of conclusive scientific data on virology and transmission of SARS-CoV-2 as of yet, and the lack of epidemiological data for case studies in the UK, all of which were outlined in detail above, our study has not attempted any calculations of risk for initial infection or for disease severity as we believe this cannot at this point in time lead to accurate results. Due to the lack of information on viral loads and infectiousness our study does not make any quantitative assumptions about the infectiousness of these aerosols. However, we present an example of one study[32] that has attempted to calculate risks of infection in Italy, based on estimates of viral emissions for SARS-CoV-2 due to aerosols/airborne transmission, and using values for infectious doses of SARS-CoV-1 (from the 2003 SARS epidemic). They used a set of scenarios in different indoor environments, assuming one infected individual enters the environment and spends some time there, and assuming the virus remains viable in the air in suspended aerosols for up to 3 hours. This study finds high risks of infections in poorly ventilated and crowded spaces.

To evaluate the efficacy of interventions imposed by the Italian government, they examined typical indoor public spaces based on either low or high ventilation rates and pre-pandemic levels of occupancy. They assumed that a single infected person entered the space and spent between 10 minutes to 1.5 hours there. They then calculated the individual risk of infection to a customer, expressed as the basic reproduction number R_0. They found that when ventilation rates are very low, the risks are equal to 3.7, 2.19, 3.64, 3.52, and 47.3, for a pharmacy, a supermarket, post office, bank, and restaurant respectively – with the restaurant scenario being particularly risky (R_0=47.3) for infections due to the long exposure time (1.5 hours), and large number of occupants (84).

This study has many limitations as it was not validated with actual epidemiological data, and it assumes infectious doses based on SARS-CoV-1 for the purpose of calculations. Despite that the fact that the actual numbers calculated for risk R_0 are not likely to be accurate, the study is useful as it demonstrates the comparative value of various interventions: increasing ventilation was found to reduce these risks substantially, even under pre-lockdown conditions: the R_0 values obtained from the simulations performed for the restaurant, pharmacy, supermarket, post office, and bank equipped with mechanical ventilation systems in the conditions before lockdown, with mechanical ventilation in operation, were still above 1, but at 1.16–5.35 they were much lower than for poor ventilation scenarios. They calculated the risks of these environments post-lockdown, when regulations were implemented to reduce infections such as queuing outside, limited time spent in the environments, and lower crowding index, and found that the R_0 numbers were substantially lower and all below 1, demonstrating that these interventions would be successful in supressing transmission due to aerosols.

Another infection risk tool has been produced by the CIRES (Cooperative Institute for Research in Environmental Sciences) at the University of Colorado Boulder to model risk of infection indoors **if people remain 6 feet (1.8m) apart** (thus also reducing overall people numbers in indoor spaces). It also relies on assumptions of infectiousness in the absence of validation data, but is useful as a guide to test different interventions and compare a certain set of scenarios[33]. New tools are continuing to emerge daily and will be considered further in phase two within the VIRAL project.

The debate on how and to what extent airborne transmission dominates transmission routes is still ongoing at the time of publishing this report, but our underlying assumption has been that as aerosols emitted by people coughing, talking, and sneezing, and possibly even breathing, do contain virions of SARS-CoV-2, and as the concentrations of these virions may rise significantly in a crowded indoor environment, the precautionary principle in the public health context suggests that it is wise to minimise exposure of bus drivers to these aerosols unless it can be proven that they do not pose a risk of infection. The prevalence of other airborne infectious diseases such as influenza in the public

32 Buonanno, G., Stabile, L. and Morawska, L. (2020) 'Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment', *Environment International*. Elsevier Ltd, 141, p. 105794. doi: 10.1016/j.envint.2020.105794 .
33 This tool can be found on: https://cires.colorado.edu/news/covid-19-airborne-transmission-tool-available

sphere suggests that this is a very desirable intervention with the potential for long term protection of bus driver's health, and the associated economic benefits due to less sickness and absence.

Our recommendations to TfL have thus been made following the principles of risk reduction, with a view to implementing interventions as quickly as possible initially, within the constantly evolving context of WHO advice and Public Health England and government regulations. We have noted that there should be work carried out to investigate the risks to passengers and propose possible mitigation strategies. There is also a need to carry out quantitative risk analysis but this is not possible at present.

3.6 The role of face masks

Face masks provide little in the way of protection to their wearer, but they have a significant effect in reducing the emission of droplets into the surrounding air as a result of sneezing, coughing, talking or breathing. Therefore, it is important for passengers to wear masks when on a bus, in order to protect other passengers and the driver. Many drivers have been reluctant to wear them, citing discomfort of wearing them for long periods, and the difficulties involved in handling masks hygienically mean that they may not necessarily provide much of a benefit to the bus drivers themselves. As the driver is isolated within their cabin, and the main effect of using a mask is to reduce the emissions from the wearer, not to protect them from emissions from passengers, it would seem reasonable not to insist on drivers wearing a mask unless they feel they wish to.

Advice on the use of face masks can be found in the following sources:

https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)31142-9/fulltext

https://www.nature.com/articles/s41591-020-0843-2

Bus Operations and Practice

There are some particular issues in relation to the operation of buses that have to be considered in order to ensure the safety of drivers and passengers and the viability of the bus system itself. From the scientific background described above, there would seem to be a need for the bus driver's cabin to be isolated from the air circulating around the bus and therefore a means was needed to determine and then reduce as much as possible the movement of air into the driver's cabin from the passenger saloon. The starting point was to consider the assault screen, which forms a physical barrier between the driver and passengers. It was also understood that further protecting the drivers via a more comprehensive assault screen would provide them with reassurance and a sense of safety.

Assault screens were previously only used as a deterrent to assaults on drivers. There was little standardisation, even within one vehicle model type. Some had large uncovered areas. All had a standard requirement for driver speech holes, but there were no guidelines on how this was achieved and the location. The assault screen provided a basic barrier between the driver and passengers, but it was designed to resist physical attacks, not resistance to the transmission of virus particles. Adaptation of these assault screens was therefore a prospect for reducing the risk of infection, but it was necessary to understand precisely how the transmission could occur. The redesign of the assault screens would have to be done in creative ways to achieve this quickly, until there was time to develop more robust long-term solutions. The start for this process was to simulate the transmission of droplets from a passenger positioned near to the assault screen.

Current ventilation and AC guidelines of TfL were reviewed and they were compared with some examples from the building ventilation regulations in the UK and from other countries. It was found that on TFL buses, the current practice was that HVAC systems were specified by performance requirement and not based on filtration or air source requirements. OEMs recently have moved towards favouring recirculated air, or a mixture of recirculated and fresh air to assist with the drive for vehicle energy efficiency and following trends in HVAC systems throughout the built environment. Coupled with the move to smaller windows in the passenger saloon, due to safety concerns, the availability of fresh air on the bus has decreased and high ventilation flow rates were no longer guaranteed.

Peak numbers of passengers in a bus pre-COVID-19 sometimes reached up to 90 passengers at a time in rush hour, when school children boarded buses between 7:30-8:30, at the morning rush hour between 8:30-9:30, and again in the evening rush hour from 16:00-19:00. Average in-vehicle journey times in London were 14.23 minutes long in 2019/20. Buses can operate 18 hours per day 365 days per year. The finances of bus operation are heavily dependent on peak hour operation. Although the peak-hour operation imposes severe costs (e.g. the peak vehicle requirement determines the overall fleet size and thus the required number of drivers), the fact is that the average occupancy of a bus in London across the network, is 16, which shows that there is a lot of spare capacity in the off-peak.

Analysis of airflow and aerosols entering the driver's cab and efficiency of potential interventions

SARS-CoV-2 when attached to small droplets (aerosols) remains airborne for long periods of time because of the very small sink velocity of aerosols. For aerosols sized 2 microns this is of the order of 10^{-4} m/s. In other words, under ideal circumstances (in stagnant air) it takes a droplet of diameter 2μm approximately 4h to reach the floor when released from a person's mouth (at a height of 1.5m above that floor). However, because aerosols are so small and light, they are transported around via turbulent airflows and may even remain suspended even for much longer periods of time. In an operating bus, turbulent airflows are ubiquitous and occur due to people movement and/or their respiration and/or their violent expiratory activities (such as talking, laughing, coughing or sneezing), due to temperature and pressure differences inside the bus or due to air entering and exiting the bus through doors and windows. Hence, it was hypothesised that aerosols with SARS-COV-2 attached to them are dispersed greatly inside a bus when released by a passenger and some may end up in the driver's cabin exposing the driver to the virus. This hypothesis was tested via numerical simulations of airflows on a bus.

A set of numerical simulations using Computational Fluid Dynamics were carried out by the UCL CEGE Engineering Fluid Mechanics Research Group (https://tinyurl.com/FluidMechanics-UCL) employing its in-house Large-Eddy Simulation code that has been verified for a large number of flows. As a multi-scale problem solved at very high temporal and spatial resolution, these simulations were run on a supercomputer to get airflow velocities and the dispersion of concentrations for "aerosol droplets", assuming passive particle transport for particles sized 2 micron that are suspended in the air. The scenarios that were simulated are summarised in Table 1 below. Cases 6, 7, 8 and 9 required several days of coding and additionally, several days of simulation time in order to fully resolve the airflow that might travel through the very small gaps of the modified assault screen (maximum gap width of 5 mm), because of the very high temporal and spatial resolution needed for the simulations.

The "worst-case spreading scenario" that was simulated is that of a passenger who stands in front of the driver's assault screen, coughing five times and then breathing normally for one minute while releasing very small respiratory aerosols (sized 2 micron). The simulations demonstrate how aerosols emitted by coughing remain suspended in air and disperse in the bus due to internal airflows. The simulations reveal the critical significance of bus door operation and that aerosols are transported more or less effectively into the driver's cab depending on the bus door operation. The simulations provide evidence that structural modifications to the assault screen reduce significantly the driver's exposure to any airborne particles containing viruses or SARS-CoV-2 and they show that ventilation, here in the form of an open cab window, very effectively flushes the aerosols out of the bus, providing confidence that ventilation can be a successful mitigation measure to help both the drivers and the passengers. The simulations enable assessment of risk reduction and mitigation strategies to lower the exposure to SARS-CoV-2 or other airborne viruses or contaminants.

Due to the urgency of the work, aerosol physics were not modelled explicitly. Due to the lack of information on viral loads and infectiousness the study does not make any quantitative assumptions about the infectiousness of these aerosols. The study is thus limited to an investigation of the potential for exposure of bus drivers to any airborne aerosols potentially containing SARS-CoV-2, before and after intervention methods are applied to the bus driver's cabin. This was achieved by simulating the airflows within the bus and the driver's cabin, including any ingress via the gaps around the assault screen, calculation of concentrations in the driver's cab and the total exposure of the driver to those concentrations during the simulation. The simulations also covered a number of realistic scenarios with respect to the main operational procedures that might have an impact on the airflow inside the bus, based on consultations with TfL, the bus operators and the unions. Operational procedures included are: opening the bus front door, opening the bus middle door, and opening the driver's cabin window; a selected number of combinations of the operations are tested. The total exposure of the driver to the exhaled/coughed air released by the passenger (which is assumed to be infected) is quantified and compared for all cases.

In total, nine large-eddy simulations of airflows and scalar transport in a public transport bus were performed. These are described briefly in **Table 1** below. Following this, cases 1 and 9 are presented in detail, comparing the concentrations and airflows between the pre-COVID scenario and the situation when all our recommended interventions are implemented.

The full results of all the simulations are presented in ***Appendix A***. On the basis of analysis of the results and calculations of exposures, the effectiveness of the various interventions has been estimated in comparison with the pre-COVID cab design (the "do nothing" scenario, **Case 1**). These interventions are presented and ranked in order of importance in **Table** 1, and additional operational scenarios are considered in **Table 3**.

Case #	Description	Front Door	Middle Door	Cab Window	Screen Gaps	Speech holes
1	Pre-COVID19	Open	Closed	Closed	Large	Open
2	Initial Intervention: Seal speech holes	Open	Closed	Closed	Large	Sealed
3	Middle door boarding	Closed	Open	Closed	Large	Sealed
4	Middle door boarding and physical distancing (passenger standing 2m back)	Closed	Open	Closed	Large	Sealed
5	Middle door boarding and cab window open	Closed	Open	Open	Large	Sealed
6	Modified Screen Design – front door boarding	Open	Closed	Closed	Small	Sealed
7	Modified Screen Design – middle door boarding	Closed	Open	Closed	Small	Sealed
8	Modified Screen Design – both doors open for boarding and alighting	Open	Open	Closed	Small	Sealed
9	Modified Screen Design – both doors open for boarding and alighting and cab window open	Open	Open	Open	Small	Sealed

Table 1 The Cases simulated using Computational Fluid Dynamics

Examples of the airflows and concentrations found in the simulations are presented below, first for the assault screen design pre-COVID and then for the design and operation recommended based on our analysis. The ventilation system is not modelled in any of the simulations. A drawing of the bus geometry is provided in Figure 1 below. Concentration is shown on the various plots as a dimensionless parameter, which is 100% at the mouth of the passenger, and a fraction of this everywhere else. Exposure is therefore expressed as a fraction of the full exposure to concentrations exhaled at the passenger's mouth (which would be eg 60 seconds exposure to 100% concentration). This method makes no assumptions about the composition of the concentration, just that it is 100% exhaled breath with a certain number of 2µm aerosols suspended in it.

Original design and operation, case S1:

The simulations consider the original gaps around the screen, no modifications made, and assume the driver's cab window is closed. Figure 2 shows isosurfaces for 1% concentration of exhaled/coughed breath. These are surfaces which correspond to a 1% concentration at that particular time, and demonstrate how far the aerosol "cloud" has travelled and how it entered the driver's cab once it was diluted with cabin air.

Figure 3 below shows contours of the aerosol concentration on a logarithmic scale in three selected horizontal planes approximately at t=60s of the S1 case, the "pre-COVID" scenario. (a) at a height just above the waist, (b) at the height of the passenger's mouth, (c) near the roof of the bus and (d) sketches the heights of these planes and the concentration contour legend. Aerosols have entered the driver's cab and remain in the cab; concentration levels are quite high regardless of the height. Aerosol concentration throughout the cab reach approximately of the original concentration coming out of the passenger's mouth (i.e. 100%). At this time the concentrations are very small as they are diluted with the air in the cab, however if the coughing and breathing continued then this concentration would increase with time.

The concentration scale is logarithmic which means that though the top of the scale (darkest burgundy, 1E+02, equivalent to air coming out of the passenger's mouth) is 100%, 1% is presented as 1E+00 (bright red), and means that in every litre of air there are 10 millilitres of exhaled breath. At the bottom of the scale (lightest grey to white, 1E-04) values of concentration are only 0.0001%. This means that in every litre of air, 0.001 millilitre would be exhaled breath (or, in every cubic metre of air, one millilitre).

It is important to note that these concentrations demonstrate that for all cases, the quantity of infectious material released by a passenger passing by for a short duration is extremely tiny. As we know now that SARS-CoV-2 is not extremely infectious (although it is more infectious than Influenza, it is far less infectious than Measles), in general there is little cause to be concerned about risk of infection from very short occasional interactions with passers-by.

Figure 4 below shows the airflows in this case, to aid understanding of how the aerosols enter the driver's cab: Streamlines are shown, of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S1 case. (a) at a height just above the waist, (b) at the height of the passenger's mouth, (c) near the roof of the bus and (d) sketches the height of these planes and the speed contour legend. The front door of the bus is open and air enters the bus from behind the passenger.

It is seen that some air flows into the cabin via gaps in the assault screen (e.g. the ticket machine at z=1.05m), along the windscreen (e.g. at z=1.50m) or through the opening in the screen for the rear-view mirror (at z=2.05m). Most of the air is deflected by the cab towards the rear of the bus.

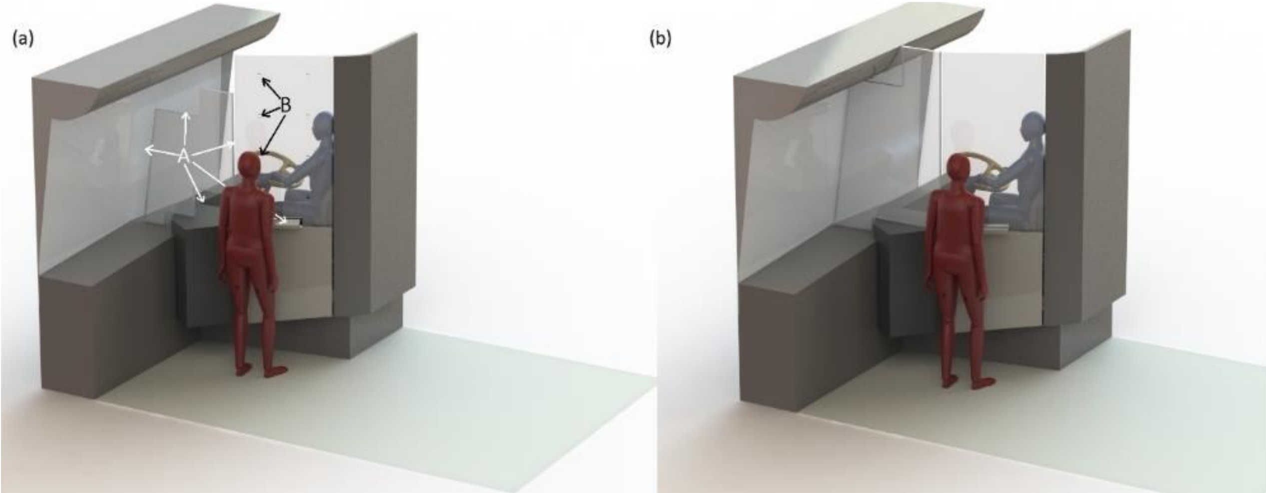

Figure 1 CAD-drawings of the passenger, driver and their cabin as imported into the Large-Eddy Simulation code depicting (a) Pre-COVID-19 cab with large gaps and (b) modified assault screen with gaps between the saloon and the cab of maximum 5mm. Capital letters A and B point to gaps in the screen or speech holes, respectively

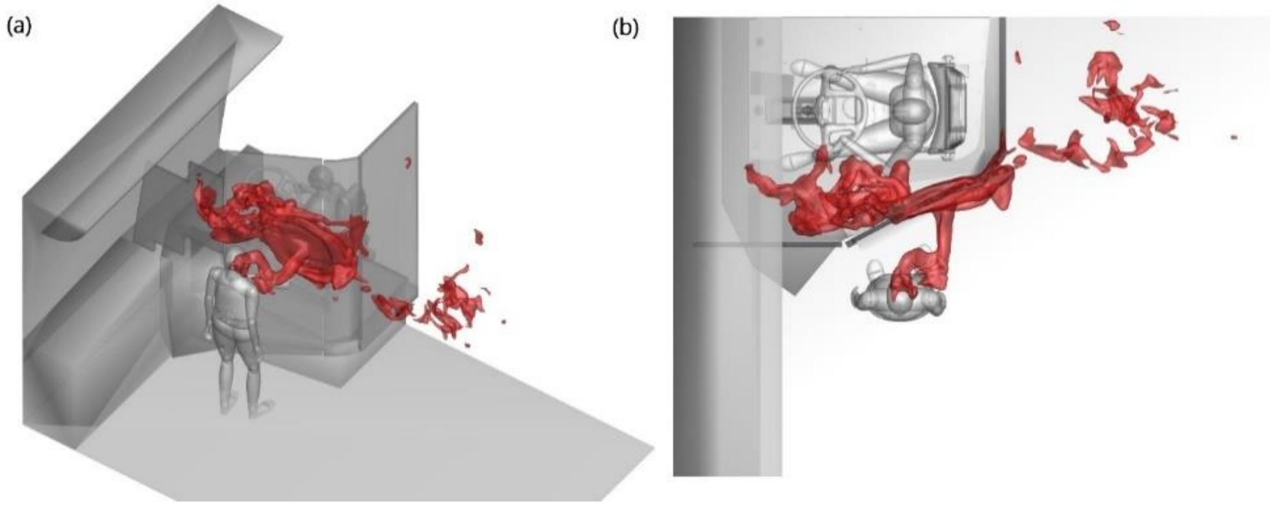

Figure 2 Isosurfaces of 1% concentration of the passenger's exhaled aerosols after 13s of real time of the S1 case, the "pre-COVID" scenario, from two different viewpoints (a) oblique view from behind and (b) view from above. Aerosols enter the cabin after the coughing episode via the speech holes and gaps in the assault screen (b) some of the aerosols are barred from entering by the screen (a) or are transported by the flow towards the rear.

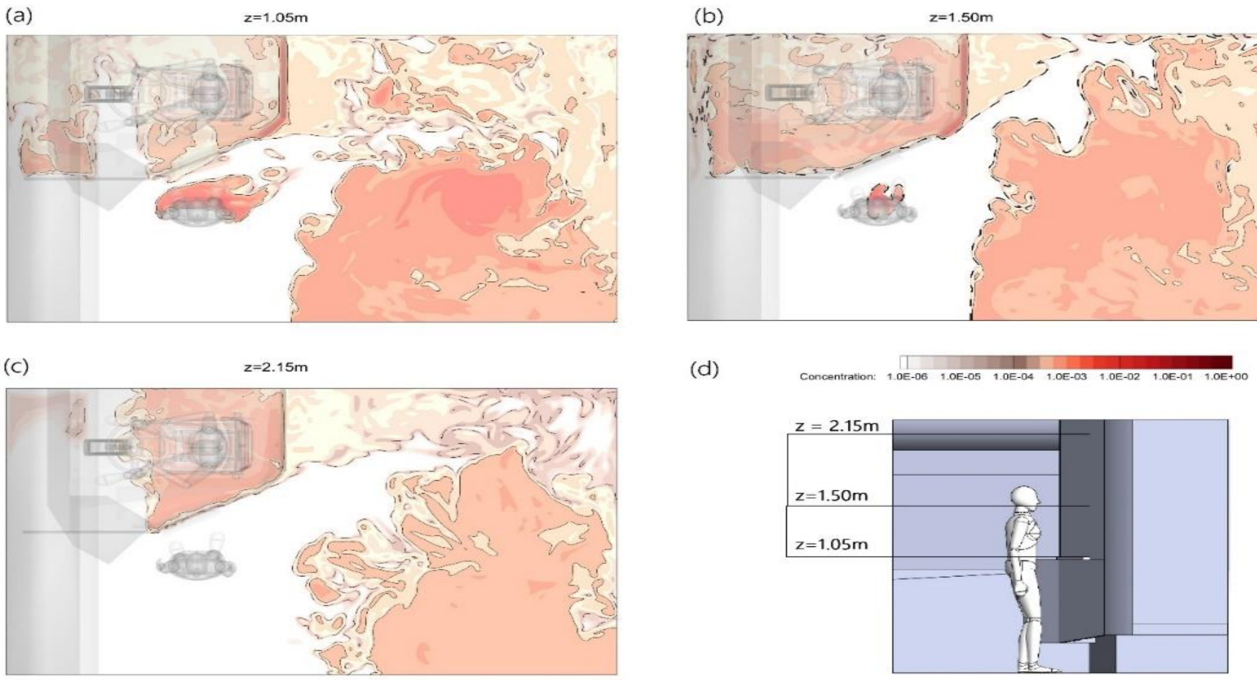

Figure 3 Contours of the aerosol concentration on a logarithmic scale in three selected horizontal planes approximately at t=60s of the S1 case, the "pre-COVID" scenario. (a) at a height just above the waist, (b) at the height of the passenger's mouth, (c) near the roof of the bus and (d) sketches the heights of these planes and the concentration contour legend. The scale increases at an increasing rate as the colour scale moves from white towards dark burgundy

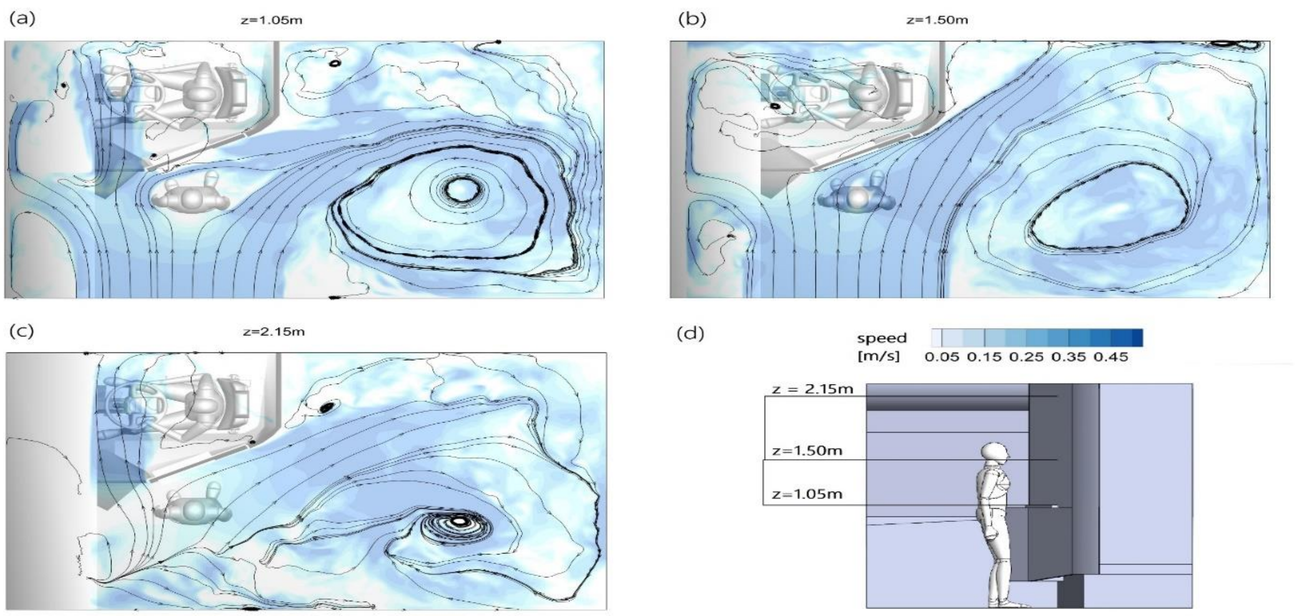

Figure 4 Streamlines of the airflow and contours of the velocity magnitude in the same three horizontal planes presented in Figure 3 above. approximately at t=60s of the S1 case, the "pre-COVID" scenario. (d) sketches the elevation of these planes and provides the speed contour legend. The front door of the bus is open and air enters the bus from behind the passenger.

Modified Assault Screen and Operation, Case 9

We now present the results for the case in which all interventions are present: The assault screen is modified so that speech holes are closed and gaps around the screen are 5 mm wide. Both doors are open in order to maximise airflow within the bus, and the cab window is also open. Figure 5 below shows isosurfaces for 1% concentration of exhaled/coughed breath. Figure 6 shows contours of the aerosol concentration on a logarithmic scale in three selected horizontal planes approximately at t=60s of the S9 case, the "best scenario" case as we recommended. Figure 7 shows the airflows in this case. Almost no air can enter the modified cabin from the passenger saloon - even with the 5mm gap all around - because of that circulation, except for near the bus roof. Because air flows into the cabin from the saloon only near the roof, no aerosols are dispersed into the cabin. There is some airflow inside the driver's cabin, into which air enters through the window and circulates around the driver. The concentrations and exposure for this case are found to be zero – they are undetectable in the simulation at all.

Note: Even in case that the driver closes the window, which they may want to do for various reasons, the resulting concentrations in the driver's cab are extremely small as can be seen in the appendix in the results of Case 8.

(a) (b)

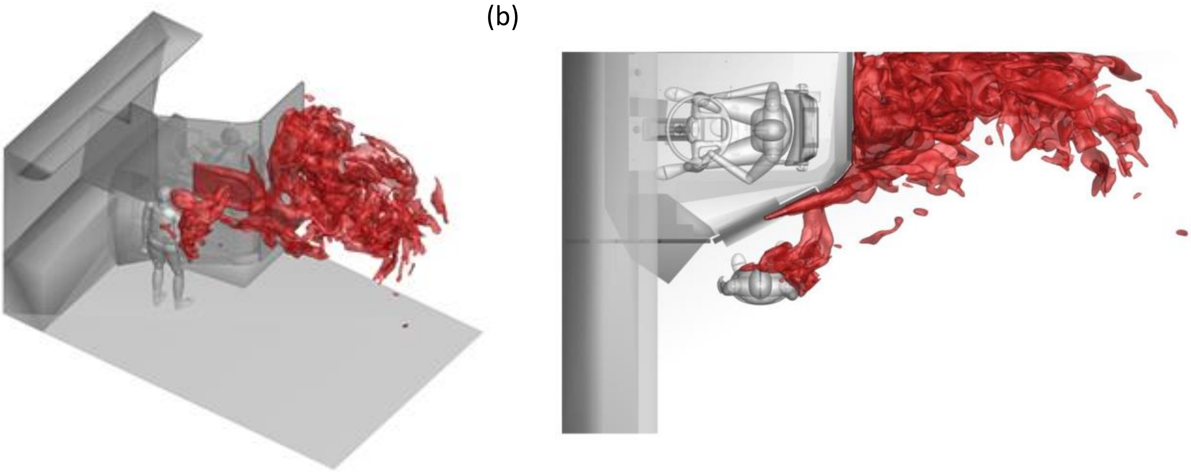

Figure 5 Isosurfaces of 1% concentration of the passenger's exhaled aerosols after the coughing episode (13s real time) of the S9 case from two different viewpoints: (a) oblique view from behind and (b) view from above. The aerosols are carried into the saloon away from the driver's cabin and do not propagate into the cabin area due to the assault screen modification and the ventilation provided by the open cabin window.

The full results and methodology are shown in Appendix A.

The simulations enabled us to calculate exposure to the exhaled/coughed breath of the passenger. Calculating actual numbers of viral particles is not possible with this method and would be based on quantities that are still unknown, so the exposure calculated is the time-weighted average exposure to the fraction of Exhaled Breath (**EB**) that travels from the passenger's mouth towards the driver's cab and becomes entrained and trapped in the cab. In a scenario where this continues, this concentration would continue to build up and the exposure would be larger. It was not feasible to run the simulations for longer, so a time-weighted average exposure over one minute is calculated. This, in order to compare effectiveness of the various interventions to one another.

Based on these results, the different cases have been analysed to determine a set of interventions and assess their effectiveness. These are described in Table 2 below, which also presents the exposure of the driver to the exhaled/coughed breath of the passenger. Table 2 describes the interventions to reduce risk to the driver, ranked according to importance and which formed the basis of our recommendations regarding the assault screens. Table 3 presents the various operational scenarios and considers how effective these are found to be.

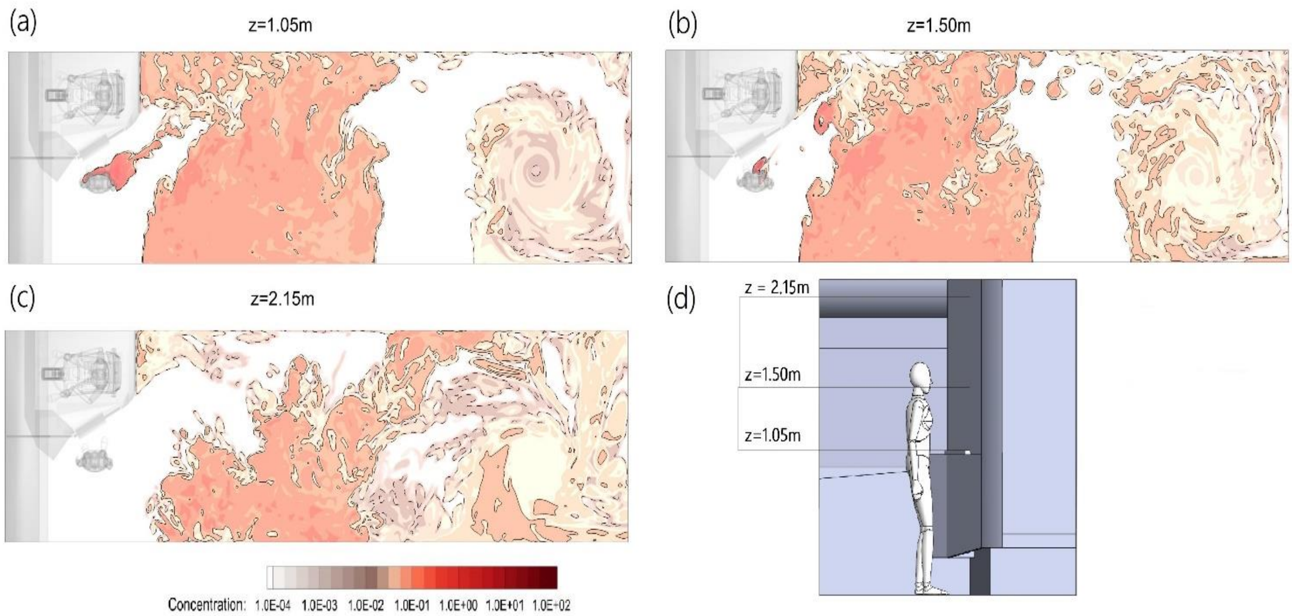

Figure 6: Contours of the aerosol *concentration on a logarithmic scale in three selected horizontal planes approximately at t=60s of the S9 case, the "best scenario" case recommended. (a) at a height just above the waist, (b) at the height of the passenger's mouth, (c) near the roof of the bus and (d) sketches the elevation of these planes and provides the concentration contour legend. The scale increases at an increasing rate as the colour scale moves from white towards dark burgundy*

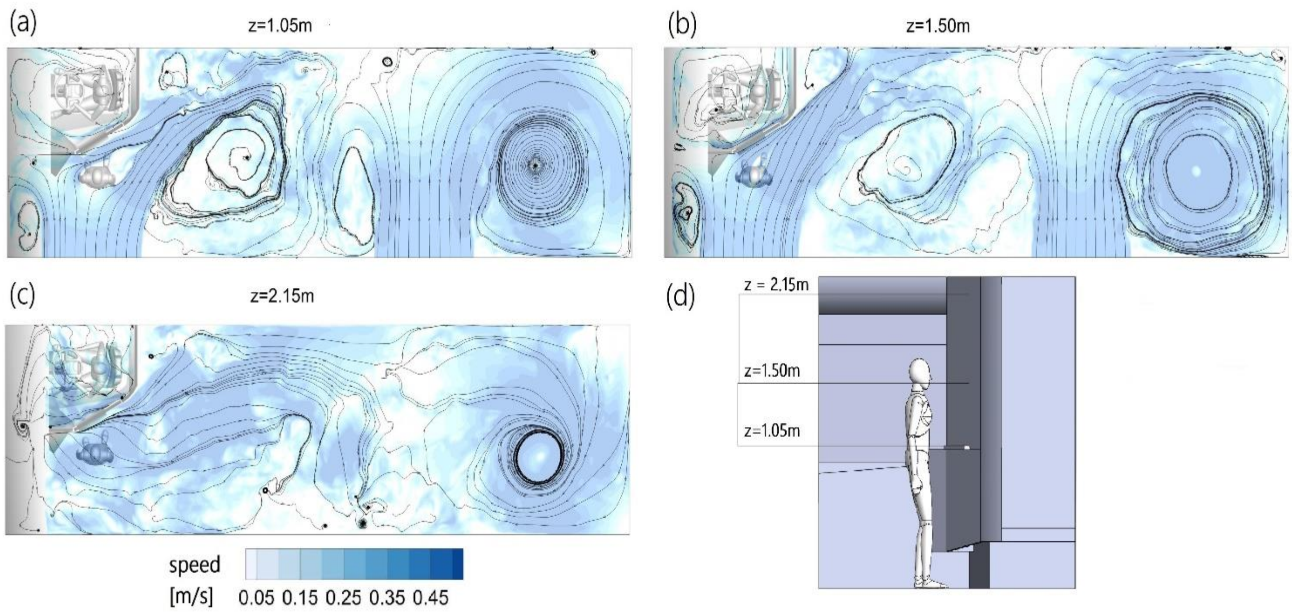

Figure 7 Streamlines of the airflow and contours of the velocity magnitude in the same three horizontal planes presented in Figure 5 above. (d) sketches the elevation of these planes and provides the speed contour legend.

Intervention	Cases	Exposure per minute: Based on the fraction of exhaled breath the driver is exposed to	Exposure per minute: expressed as a fraction of the exposure in Case 1, pre-COVID-19	Recommendations
Modifications of Assault screens such that the gaps around them to be no more than 5 mm	**6** **7** **8** **9**	0.25% 0.8% 0.3% 0	3% 10% 4% 0	The best passive protection measure, this does not require any behaviour changes by either drivers or passengers. The modifications are effective for all operational scenarios re: windows and doors. Recommend this becomes a permanent change in driver's cab design at the vehicle manufacturing stage
Opening the window in the driver's cab	**5** **9**	0.02% 0	0.3% 0	Highly effective and practical, to be implemented as soon as possible on all buses. May be at times temporarily problematic on unsafe roads or when raining but will offer effective protection for the driver on any bus that has not yet been modified, regardless of door operations. Windows can be opened periodically for short times and will offer strong protection as long as assault screens are in place. Precise airflows through windows will depend on outside wind and temperature.
Sealing the assault screen speech holes	**2** **3** **4**	7.4% 17.9% 18%	94% 226% 227%	This measure is effective against direct spray from droplets. However, it is only marginally effective on its own for protection against aerosol concentrations. In comparison with the pre-COVID scenario this will have reduced overall concentrations only by 6%. In some flow scenarios this intervention had no impact.

Table 2 Interventions to reduce risk to the driver, ranked according to importance

Operational scenario	Cases	Exposure per minute: Based on the percentage of exhaled breath the driver is exposed to	Exposure per minute: expressed as a percentage of the exposure in Case 1, pre-COVID-19	Recommendations
Front Door boarding	**2** **6** **8** **9**	7.4% 0.25% 0.3% 0	94% 3% 4% 0	Deemed safe in cases 6, 8 and 9, due to the improved airflow patterns on the bus, in the case that screens are modified to no more than 5 mm gaps. Also deemed safe when the driver's cab window is open – from Case 5 we learn that opening windows will be effective even in the absence of assault screen modification, but the window would need to be open most of the time, which may not be practical in cold weather
Opening both doors	**8** **9**	0.3% 0	4% 0	Deemed safe in the case of the modified assault screen and even more effective when additionally opening the driver's cab window.
Middle door boarding, with or without modified assault screen	**3** **7**	17.9% 0.8%	226% 10%	This intervention is not desirable where aerosols and airborne transmission are concerned, due to aerosols being blown directly into the driver's cab due to the airflow patterns on the bus. Even when the assault screen is modified, this is less effective than the cases of front door/both doors open that are shown above
Physical distancing: Maintaining 2m distance between passenger and driver's cabin in the case of middle door boarding	**4**	18%	227%	Physical Distancing is not an effective measure on its own. Suspended aerosols still entering the driver's cabin due to airflows. Although they took a longer time to enter the cab, the total exposure for the driver would still be higher than for other cases. No difference at all compared with the identical case 3 where the passenger is close to the driver.

Table 3 Additional Operational scenarios considered

Notes:
We were aware that there were a number of additional scenarios that may be of interest but simulating those is a very lengthy process (measured in weeks) and it was estimated by our team to be of limited additional value and only likely to lead to delays in implementing the interventions that were recommended based on our professional expertise. We therefore focussed on what were considered to be the worst case – albeit untypical – scenarios to enable us to recommend as safe a solution as practicable.

The analysis has not considered ballistics of larger droplets as it is known that these will settle on surfaces and on the floor and were not posing a risk to the drivers behind the assault screens in any case. The analysis has considered the worst-case scenario of airborne transmission of the disease via tiny aerosols, assuming there is a risk that if present in high concentrations these aerosols may be infectious. The numbers of aerosols produced in this study by a passenger during one minute is very small and these are extremely unlikely to be infectious on their own in the case of SARS-CoV-2, which is not considered a highly infectious disease. These aerosol concentrations are indicative of the potential risk to drivers (or passengers) in the worst-case scenario that an infectious passenger with high viral loads (a "super-spreader") boards the bus and remains on it for a long journey, in the absence of adequate ventilation with fresh air so that these aerosols continue to build up over time. When precise values for viral loads and infectious doses emerge in the future, it would be possible to calculate longer term exposures and risk of infection, accounting for ventilation, airflows throughout the bus, numbers of passengers and their journey duration.

Initial Recommendations

6.1 Modifications to the assault screen

The simulation work described in Section 5 and Appendix A shows that air ingress into the cabin from the bus saloon is reduced by over 99% if the assault screen is adapted to seal off the speech holes, and extended in such a way as to have a gap of 5mm all around. This is because the air pressure within the cabin, generated by the heating, windscreen demisters, air conditioning supply in the cabin, or the driver's window being open, is sufficiently positive to preclude ingress from the saloon through the small gaps. The results also show the impact of the modifications and operational scenarios on total exposure of the driver – to whatever is exhaled or coughed by the passenger, be it aerosols containing SARS-CoV-2 or any other biological pathogen – and the extent in which these are reduced by almost 100%.

However, part of the issue is the sense of safety felt by the drivers and it had become clear that this was not helped by the presence of a small gap, and so pending the final results of our work the decision was taken by TfL to attempt to close the gaps completely. This was not considered a high priority by our team as this raises other issues, such as condensation resulting from the diver's breathing, and the need to ensure that the CO_2 level within the cabin is maintained at or below a safe threshold, in order to avert drowsiness, and to prevent mould growth. Good air quality for the drivers must be achieved by ensuring fresh air going into the driver's cabin and the first step was to recommend opening windows, until a more thorough retrofit was carried out that involved modifying the ventilation systems for drivers to have fresh air feeds across the fleet. This retrofit was considered by our team to be a higher priority and of more value than sealing the assault screens entirely. Examples of the original screen and a modified screen are shown below in Figure 8 and Figure 9; pictures from TfL.

It is recommended that future bus fleets are designed at the point of manufacture to have a robust fully enclosed cab for the drivers to protect them both against physical assault and against any form of biological or chemical risk whether intentional or not. The cab should not allow ingress of sprays or fluids, and air and should protect from physical assault as well, yet still be clear and transparent to allow good visibility for the driver. This recommendation is not without social and financial costs and it is made on the basis of the specific conditions in London where passenger numbers are high and number of daily journeys is high, and may not be appropriate, feasible or necessary elsewhere in the UK where risks could be much lower. Of particular concern is the issue of equitable accessibility – for example, the loss of speech holes may make it difficult for communications to be satisfactory for people with hearing difficulties, and it might be necessary to provide a suitable electronic communication system to mitigate this; this may need to be installed elsewhere and not on the assault screen.

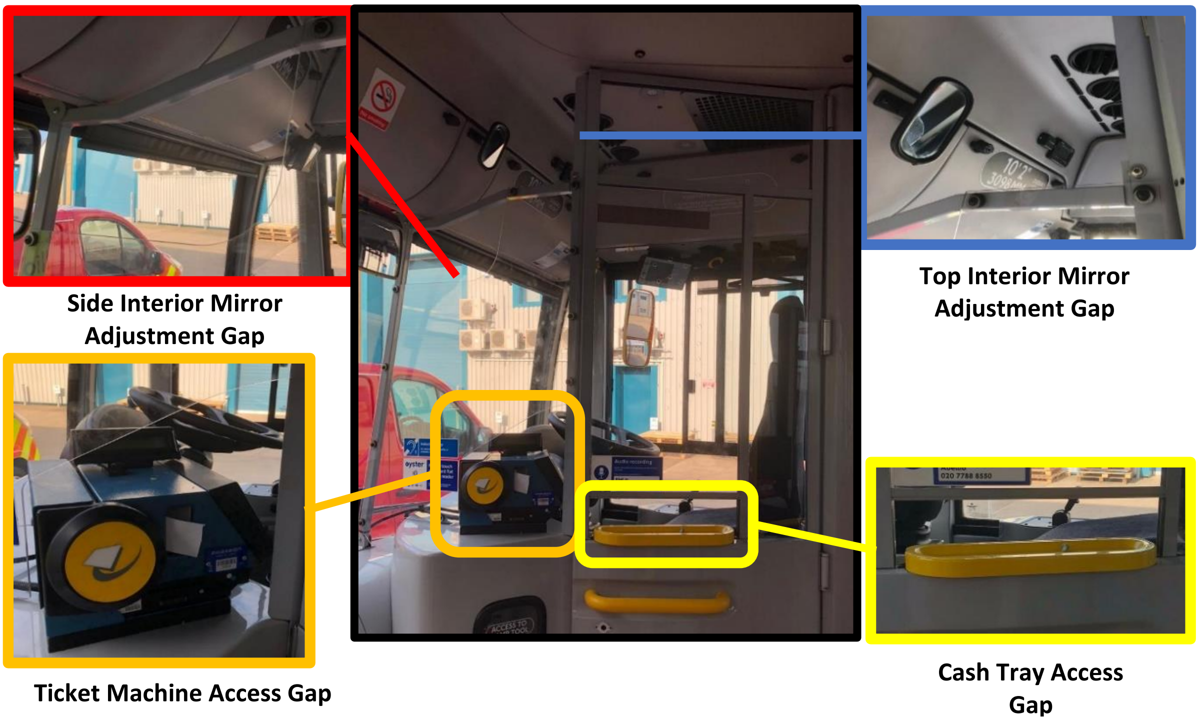

Figure 8 Original assault screen on an E200 model bus

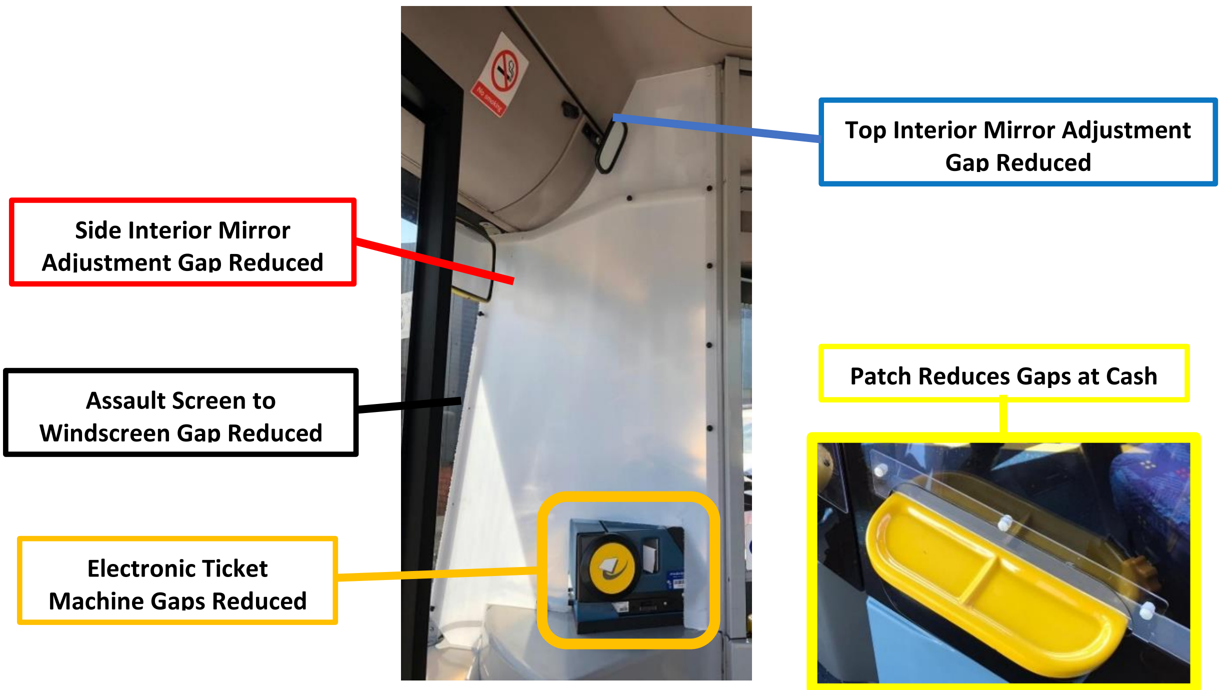

Figure 9 Modified assault screen on an E200 model bus

6.2 Ventilation

Most Air Quality (AQ) guidelines in the UK and in Europe use CO_2 as a proxy for good AQ and do not refer specifically to bacterial counts, viruses or fungi. However, in 2004, perhaps following from the 2002-2004 SARS outbreak, 'Indoor Air Quality (IAQ) Control in Public-use Facilities, etc. Act/Korea' was amended to control IAQ in public facilities, including underground subway stations, underground shopping malls, medical institutions, large shops, movie theatres and newly-built multiunit housing. These must now comply with AQ limits on indoor pollutants such as PM10, carbon dioxide CO_2, formaldehyde, and carbon monoxide CO, as well as total airborne bacteria[34]. IAQ guidelines for public transport have also been enforced since 2014. Guidelines on indoor air quality in Singapore from 1996 also include recommended limits for fungal and bacterial counts[35]. There is evidence of adherence to IAQ guidelines on the public transport network in Taiwan as well, which was found to meet recommended standards in an environmental studiy of the metro[36], but to fall short of these standards on coaches [37]. Guidance published in Hong Kong in 2003 introduced recommended standards on IAQ of public transportation and described in detail how to achieve these, leading also to IAQ monitoring efforts on their systems[38]. To the best of our knowledge, such general guidance does not yet exist within the transport system in the UK.

Industry HVAC bodies specialising in building ventilation controls have also been updating their guidelines in the past few months, as a first response with a view to updating them further in the coming months. A few examples of such guidance:

- The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) : https://www.rehva.eu/activities/covid-19-guidance?no_cache=1
- https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_ver2_20200403_1.pdf
- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) position document on infectious aerosols: https://www.ashrae.org/File%20Library/About/Position%20Documents/PD_InfectiousAerosols_2020.pdf
- The Chartered Institute of Building Services Engineers in the UK (CIBSE), is the chief relevant UK institution whose membership includes leading experts on ventilation and air quality in buildings. They regularly produce ventilation and environmental design guidance and are regularly updating their recommendations for possible responses by building services engineers to COVID-19 : https://www.cibse.org/Coronavirus-(COVID-19), https://www.cibse.org/coronavirus-covid-19/coronavirus,-sars-cov-2,-covid-19-and-hvac-systems

As part of this project, existing HVAC standards on the TfL buses were reviewed. These standards focus on passenger comfort requirements and were recently planned by TfL to be updated in order to provide better thermal comfort. It was determined that successive adaptations to window sizes to ensure safety for child passengers have potentially resulted in poorer ventilation on the buses. There is scope to update those to follow best practice and current methods from the building industry, and to go one step further than current standards, to address minimising transmission from infectious diseases.

We recommend adapting standards from ASHRAE standard 62 as it is the most well-developed and widely accepted standard in the built environment, has sophisticated analyses of thermal comfort, CO_2 levels, metabolic rate etc. It

[34] Report of the Ministry of Environment, Republic of Korea, 2015, page 14. http://eng.me.go.kr/eng/file/readDownloadFile.do?fileId=115224&fileSeq=1&openYn=Y

[35] Guidelines for Good Indoor Air Quality in Office Premises, Institute of Environmental Epidemiology, Ministry of the Environment (1996) https://www.bca.gov.sg/greenmark/others/NEA_Office_IAQ_Guidelines.pdf, Page 44

[36] Chen, Y. Y. *et al.* (2016) 'Indoor air quality in the metro system in north Taiwan', *International Journal of Environmental Research and Public Health*. MDPI AG, 13(12). doi: 10.3390/ijerph13121200.

[37] Chiu, C. F., Chen, M. H. and Chang, F. H. (2015) 'Carbon dioxide concentrations and temperatures within tour buses under real-time traffic conditions', *PLoS ONE*. Public Library of Science, 10(4). doi: 10.1371/journal.pone.0125117.

[38] Kwon, S.-B. *et al.* (2008) 'Study on the Indoor Air Quality of Seoul Metropolitan Subway during the Rush Hour', *Indoor and Built Environment*. SAGE Publications Sage UK: London, England, 17(4), pp. 361–369. doi: 10.1177/1420326X08094683.

ensures thermal comfort and alertness are accounted for, using CO2 as indicator of ventilation rates whilst recognising that this is limited in addressing contaminants that may need to be removed. The BS62.1-2019 provides rationales for rates of ventilation infiltration with fresh air, for a range of occupancies and settings. However, public transport and drivers are excluded from these guidelines. The most useful guidance that can be found is that in many situations, ventilation rates of 10 L/s/person are recommended due to high levels of activity and possibility of contaminants in the space (for example sports halls, nail salons, manufacturing).

There has been ample research on the impacts of thermal comfort and ventilation rates on building occupant satisfaction and performance. A 2017 review of the literature[39] finds that there are significant improvements for outdoor air supply rates of between 10 and 30 L/s/person on performance of office workers, and school children. The following technical FAQ explains rationale for allowable levels of CO_2 in an occupied space. It refers only to the removal of body odour and is explicitly not designed to remove contamination.
https://www.ashrae.org/File%20Library/Technical%20Resources/Technical%20FAQs/TC-04.03-FAQ-35.pdf

Considering all the evidence available to us, we made the following specific recommendations:

a) Avoid recirculation of air between the saloon and the driver's cab, so that the air in the cab is kept separate to the passenger saloon in terms of the air supply.
b) In order to ensure safe CO_2 levels inside the cab, the cab ventilation system must provide high standards of indoor air quality. We recommended that this be provided by a demand-controlled ventilation system that automatically keeps CO_2 levels in the cab below 800 ppm (or, 400 ppm above average outdoor values in London, whichever is the lower at all times. Alternatively, we recommend that a continuous fresh air feed of at least 10 litres per second be supplied, that cannot be disabled by the driver while the cab windows are closed. These measures will help to ensure driver alertness.
c) There is still work to do on the passenger side. There is a need for more research into ventilation systems and engineering controls that may help prevent viral spread in indoor air, especially as in colder/wetter weather it becomes more challenging to keep windows open in the passenger saloon and to ensure fresh air.
d) In the absence of more explicit guidelines for transport systems in the UK, we recommended that TfL considers using the ASHRAE Standard 62.1-2019 for building HVAC systems. Following this standard, we recommended that TfL considers fitting the ventilation system for the saloon with a particulate matter filter or air cleaner of MERV (see eg https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating-1) 11 in accordance with ASHRAE Standard 52.2, noting that this topic needs to be researched explicitly and that there may be other engineering controls that may help. New research is constantly being published on this topic.

6.3 Cleaning practice

SARS-CoV-2 is able to persist on surfaces and remain viable for some time, however, it is a relatively easy virus to inactivate with soap, detergents, alcohol, bleach and common disinfectants such as chlorhexidine and benzalkonium chloride, contained in many household cleaning products such as surface wipes[40] [41].
Globally, a number of organisations have released lists of products suitable for inactivating SARS-CoV-2:

a) The United States Environment Protection Agency has published a list of recommended agents for cleaning during COVID-19 (https://www.epa.gov/pesticide-registration/list-n-disinfectants-use-against-sars-cov-2)

[39] https://www.sciencedirect.com/science/article/pii/S0360132316304449 Wargocki & Wyon (2017)
Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork, *Building and Environment*, Volume 112, 2017, Pages 359-366, https://doi.org/10.1016/j.buildenv.2016.11.020
[40] Kampf et al (2020) , https://www.journalofhospitalinfection.com/article/S0195-6701(20)30046-3/fulltext
[41] Chin et al (2020) https://www.thelancet.com/journals/lanmic/article/PIIS2666-5247(20)30003-3/fulltext

b) The European Centre for Disease Prevention and Control (ECDC): (https://www.ecdc.europa.eu/sites/default/files/documents/coronavirus-SARS-CoV-2-guidance-environmental-cleaning-non-healthcare-facilities.pdf)
c) Public Health England (https://www.gov.uk/government/publications/covid-19-decontamination-in-non-healthcare-settings/covid-19-decontamination-in-non-healthcare-settings)
d) As the virus is inactivated by cleaning products used by cleaning contractors, it is not necessary to make any changes to cleaning products. Some premises have opted to use cleaning agents that are specifically antiviral as well as UV light and fogging or misting. While these are beneficial in the healthcare setting where they are routinely used by trained staff and where contamination is known to be high, there is little benefit that these practices will bring to the office or vehicle setting. The real benefit will come from implementing more frequent thorough cleaning regimes using the products already employed.

Globally, a number of organisations have published guidance for good cleaning practice during COVID-19 that is effective for eliminating SARS-CoV-2:

a) The UK Government has produced some guidance on good cleaning practice in public transport vehicles: https://www.gov.uk/government/publications/coronavirus-covid-19-safer-transport-guidance-for-operators/coronavirus-covid-19-safer-transport-guidance-for-operators
b) The ECDC has also published guidance on the cleaning of public transport vehicles: https://www.ecdc.europa.eu/sites/default/files/documents/COVID-19-public-transport-29-April-2020.pdf
c) The US Centres for Disease Control have provided guidance for the cleaning of public transport vehicles: https://www.gov.uk/government/publications/coronavirus-covid-19-safer-transport-guidance-for-operators/coronavirus-covid-19-safer-transport-guidance-for-operators

It is important to identify contamination hotspots on high-touch surfaces and implement more frequent cleaning regimes for these sites. These will include surfaces that passengers touch frequently, such as grab poles.

6.4 Driver Actions

In addition to increasing the levels of fresh air entering the driver's cabin by opening the window, it is advisable that drivers use antimicrobial surface wipes to wipe down the surfaces that the drivers touch frequently (e.g. steering wheel) to be used when drivers change over at the end of a shift.

The drivers should also use hand sanitiser and, where practical, may wear face masks and be trained in how to effectively use both. This would include instruction on how to put on, wear, remove and dispose of masks:

a) Disposable masks: (https://www.who.int/images/default-source/health-topics/coronavirus/masks-infographic---final-(a4---web---rgb).png?sfvrsn=cb3153cf_11).
b) Cloth reusable masks: (https://www.who.int/images/default-source/health-topics/coronavirus/clothing-masks-infographic---(web)-logo-who.png?sfvrsn=b15e3742_16)

Drivers should spend as little time as possible beyond the normal safety and security checks in the saloon and avoid touching surfaces within it. If the driver does need to touch any surfaces or objects within the saloon (e.g. to collect rubbish, to open windows), they should sanitise their hands immediately afterwards. The driver should wear a mask when spending time in the saloon. Where possible, breaks should be taken in the cabin or outside of the bus. It is not advised that the driver sits in the passenger saloon or consumes food in it as this may pose a higher risk of infection.

Summary

1. This work was commissioned by TfL because consideration of driver's protection was deemed necessary, due to the potential for prolonged exposure to airborne viruses and pathogens such as, potentially, SARS-CoV-2. We do not yet know precisely how much SARS-CoV-2 is present in aerosols or what the precise risk of infection is.
2. Droplets will settle on surfaces around the passenger as is well known. However, in additional to droplets, aerosols are generated by human expiratory activities and these remain suspended in air and can be transported around a bus via local airflows. These can be simulated and predicted using Computational Fluid Dynamics.
3. A set of recommendations has been made with the aim of reducing this risk to London drivers in particular as much as is practically possible, further to interventions already initiated by TfL. Polycarbonate dividers or screens are only marginally protective against aerosols and are not sufficient on their own to protect against airborne transmission of SARS-CoV-2.
4. Buses in large cities are a unique indoor environment that is confined and often crowded at rush hour or in tourist season and, if poorly ventilated there is potential for airborne transmission of infectious diseases which may pose a risk to drivers due to their prolonged exposure times.
5. There may be a risk to passengers too, if they are on board for long journeys. It is impossible at present to estimate how long is "a long journey", but assessments in the literature consider that exposure to an infected person without a face covering of over 15 minutes may increase risk. It is important to note that most passengers will not be infected at all. Current guidelines on social/physical distancing ensure that overall passenger numbers are low so that the risk of being in the presence of an infectious passenger is greatly reduced and the risk of infection even if such a passenger is present is also greatly reduced. This situation may change in the future, and the problem of asymptomatic carriers is concerning, and it is thus recommended that passive measures to reduce airborne transmission are adopted. At the moment the most practical and simple recommendation is that windows are left open in the passenger saloon, though this may prove to be challenging for passengers in the winter.
6. Quantifying exposure risks considering both drivers and passengers wearing face masks was beyond the scope of this study and this is recommended for further study in order to better understand their effectiveness in reducing risk to passengers and to drivers in other industries that do not have built-in protection screens. However, it is clear, given all the new understanding gained in the scientific community around airborne transmission in the past few months, that it would be best to continue to require all passengers to wear face masks.
7. Regardless of any mechanical or physical interventions to reduce risk, it is recommended that in the medium-term targets for Indoor Air Quality (IAQ) standards on public transport are developed and adopted. This, due to the high number of daily passengers, some of whom have long journey durations (>1hr if commuting from zones 4 and beyond) and the prevalence of infectious diseases such as influenza and the common cold in the population every winter season, which carry large economic costs and also cost lives. The emergence of highly infectious and more dangerous diseases in the UK and around the world in the past two decades, such as SARS-CoV-2, SARS, H1N1 (swine flu) or MERS, all indicate that it is very timely to invest efforts towards maintaining healthy and safe indoor air on public transport.

Proposals for future research:

The results of this work have yielded a number of questions about the operation of buses in a COVID world. First, this work was very specific to the situation pertaining to the driver and the cabin in which they work. Subsequent projects are underway to examine the situation in the rest of the bus – the passenger saloons on both upper and lower decks.

Secondly, the isolating of the driver's cabin from the main passenger saloon within the bus has implications for air quality within the driver's cabin, especially in periods of inclement weather, when the likelihood will be that the driver would want to close their window. Therefore, these implications need to be explored urgently, so that air quality is assured to be appropriate, not least to ensure that drowsiness due to a build-up of Carbon Dioxide in the cabin is avoided. Research is now underway to assess the viability of having CO_2 detectors installed and connected to the air circulation system in the cabin in order to maintain and control the cabin air quality.

Thirdly, the finding that ventilation is key to reducing the risk of infection transmission means that we should investigate the current movement of air within and through buses, and consider whether the current situation, which predominantly relies on natural ventilation within the vehicle (i.e. using ingress of external air via the windows and doors) is sufficient, and if not how some form of mechanical system should be specified to ensure that the ventilation rates are sufficient. This potentially has a profound implication for the transition to fully electric buses, as the energy requirement for such a system is at odds with the capacity to provide energy for this and to drive the bus. Therefore, an essential piece of work is required to define the HVAC requirements together with the energy implications and potential solutions.

Fourthly, it is clear that there is still a lack of knowledge about the transmissibility of the virus in enclosed situations, such as buses and other interior public spaces, and the actual safe physical distancing that should be recommended. Therefore there is a need for research to be undertaken in an environment that can realistically represent these environments, with a range of temperature, humidity and air handling specifications, with appropriate analysis of suitable (benign) virus surrogates. Such a facility does not yet exist, and a strong recommendation from this research is that it is an urgent requirement.

Finally, there is a need to establish whether the present financial models, based on highly intense operations in the peak hours, are actually sustainable in a situation where the number of peak hour passengers on a bus may need to be reduced, either because of a reduction in passengers due to changes in working patterns, or specifically to reduce the maximum number of passengers on a bus in order to improve air circulation within the passenger saloons.

Acknowledgements:

The authors wish to thank the MET Office for their assistance in running these highly computationally expensive simulations on their computing system. The authors would like to specifically express sincere gratitude to Dr. Chris Jones and Dr. Sam Cusworth for all their work in porting the LES code to their system and managing the running of the simulations under unprecedented circumstances. The authors also wish to acknowledge the use of the UCL Kathleen High Performance Computing Facility (Kathleen@UCL), and associated support services, in the completion of this work.

Appendix A – CFD Simulations

MODEL DESCRIPTION

Airflow

In this study, the in-house code Hydro3D is employed for the large-eddy simulation (LES). Hydro3D has been validated for and applied to several flows and scalar transport of similar complexity to those reported here [*Kim et al., 2013, Ouro et al., 2019*]. The code is based on a finite-difference method on a staggered Cartesian grid. The filtered Navier-Stokes equations for incompressible, unsteady and viscous flow are solved as given below:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \frac{\partial (2\upsilon S_{ij})}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (2)$$

where u_i and u_j are spatially resolved velocity vectors (i and j = 1, 2, and 3 represent x-, y- and z-axis directions, respectively) and similarly, x_i and x_j represent the spatial-location vectors in the three directions; *p* is the spatially resolved pressure divided by the flow density; υ is the kinematic viscosity; and S_{ij} denotes the filtered strain-rate tensor and is calculated as $S_{ij} = 1/2(\partial u_i / x_j + \partial u_j / x_i)$. The subgrid-scale (SGS) stress τ_{ij} is defined as $\tau_{ij} = -2\upsilon_t S_{ij}$. In this study, the wall-adapting local eddy viscosity (WALE) proposed by *Nicoud* [1999] is used to calculate the eddy viscosity, υ_t, and model the SGS stress.

The convection and diffusion terms in the Navier-Stokes equations are approximated by 4th-order accurate central differences. An explicit 3-step Runge-Kutta scheme is used to integrate the equations in time, providing 2nd-order accuracy. A fractional step method is employed, i.e. within the time step convection and diffusion terms are solved explicitly first in a predictor step which is then followed by a corrector step during which the pressure and divergence-free-velocity fields are obtained through a Poisson equation. The latter is solved iteratively through a multi-grid procedure. Details of the code are reported in *Cevheri et al.* [2016] and *Ouro et al.* [2019].

Scalar Transport

Within Hydro3D the transport of a passive scalar can be described by solving the filtered scalar transport equation at each timestep:

$$\frac{\partial C}{\partial t} + u_i \frac{\partial C}{\partial x_i} = (D + D_t)\frac{\partial^2 C}{\partial x_i^2} + S_i \quad (3)$$

where, C is the scalar concentration, t is time, u_i is the velocity in the i, j, k-directions, x_i is the coordinate in space in the i, j, k-directions, D is the molecular diffusivity, or the ratio of molecular viscosity to the molecular Schmidt number (Sc), $D_t = \nu_t / Sc_t$ is the Sub-Grid Scale (SGS) turbulent diffusivity in which, ν_t is the SGS viscosity, and Sc_t is the turbulent Schmidt number. S_i is a source term that accounts for gravity resulting in a sink velocity of the droplets and is only non-zero if $i = k$. The settling velocity is calculated using Stoke's Law which is valid for very small aerosols/particles.

A 2 micro-meter particle size is chosen following Morawska et al. (2009). They measured the droplet size distribution during different respiratory activities of humans and reported a range <5.5 µm. Instead of using a distribution, we chose 2µm as a characteristic/mean aerosol size for simplification. The aerosol settling velocity based on the 2µm aerosol size is approximately 0.11 mm/s, according to Stokes' law. The Schmidt number, which represents the molecular diffusion of droplet particles in air, was chosen as 500 based on a study of molecular diffusivity of airborne aerosols by Morency and Halle (2012). The turbulent Schmidt number was chosen as 0.7 similar to Ouro et al. (2018). However, in large-eddy simulations the subgrid-scale diffusion is very small and the transport of the scalar in an Eulerian framework is very similar to the transport in a Lagrangian framework, because the main mode of transport is advection.

Computational Setup

In total nine large-eddy simulations of airflows and transport and dispersion of aerosols in a public transport bus are performed. The different scenarios are provided in Table 1. As mentioned above, the main objective of the simulations is to obtain evidence of a bus driver's potential exposure to covid-19 aerosols (or droplets) for selected worst-case scenarios. Nine such scenarios are identified, and these involve a passenger (considered to be an infectant) coughing just outside the bus driver's cabin. The first simulation (S1) includes the original geometry of the bus, an open front door through which air flows into the bus, a passenger that has just boarded the bus and stands in front of the bus driver's cabin's assault screen, with its original specification (pre-covid-19), behind which the bus driver sits in their seat. This scenario is depicted in Figure 1(a) in which the arrows originating from A highlight the noteworthy gaps in this screen and the arrows originating from B point towards some of the assault screen's speech holes. Figure 1(b) presents the setup for which the bus driver protection interventions have been included, such as closing above mentioned gaps around the assault screen (to a pre-specified maximum gap of 5mm) or sealing up all speech holes in the screen.

The computational domain is presented in Figure 2. The virtual bed elevation (z=0) is set at the bottom of the bus, which is indicated by the grey horizontal plane. The macro-geometry details from real as-built bus CAD models supplied by collaborator Transport for London (TfL) were re-modelled to enable meshing algorithms to be more readily applied. This re-modelling involved removing complex micro-geometry details such as fillets and bolt heads, as well as simplifying elements such as the driver's cab-door where the frame geometry was incorporated into the door geometry itself. The resulting CAD geometry for the various operational scenarios that were simulated, as detailed in Table 4, are shown in Figures 1a and 1b. The process of meshing and importing the CAD geometry into Hydro3D followed the methodology laid out in *Stubbs et al.* [2018].

All simulations are carried out at a relatively high bulk Reynolds numbers of $Re_D \approx 50{,}000$, based on the airflow velocity (0.5m/s) through the door into the bus and the door width (≈1.5m) or jet Reynolds number $Re_j \approx 3600$, based on the maximum airflow out of the passenger's mouth (≈8m/s) and the mouth opening (≈1cm), respectively.

Dirichlet inflow conditions are prescribed at the two bus doors (indicated in Figure 2) and open-boundaries (zero-gradient Neumann boundary condition) are placed at the East end of the domain. The no-slip condition is applied on all solid surfaces of the bus and occupants (passenger/driver). In order to achieve the no-slip condition on non-Cartesian boundaries (occupants, all geometrical details) of the bus, a refined version (*Kara et al.*, 2015c) of the direct-forcing immersed-boundary method (IBM) proposed by *Uhlmann et al.* [2005] is used.

The passenger and the driver's respiratory actions are prescribed using Dirichlet conditions in the form of volumetric flow rates into and out of the two humans' mouth (exhaling, coughing) and nose (inhaling). A volumetric flow rate of 500ml/s is assumed and the passenger's and driver's respiratory flowrates over the course of 60s is plotted in Figure 3.

Exposure

We are concerned with the total exposure to the passengers Exhaled Breath, or, EB, over one minute. Total exposure was calculated as the sum of exposure at each timestep as follows:

$$\sum E = \int_{t_s}^{t_s+30} C\, dt,$$

where, E is the exposure at any given timestep, t_s is the time when concentration was detectable in-front of the driver's mouth, C is the scalar concentration at any given timestep, and dt is the difference in time from any given timestep to the previous.

Concentration is shown on the various plots as a dimensionless parameter EB, which is 100% at the mouth of the passenger, and a fraction of this everywhere else. This method makes no assumptions about the composition of the concentration, just that it is 100% Exhaled Breath with a certain number of 2µm aerosols suspended in it.

The exposure was calculated based upon the scalar concentration found 5 cm in-front of the driver's mouth (x=1.12, y=1.90, z=0.81 within the domain) from the point in time when EB concentration was detectable and then onwards for 30 seconds. These exposure results were then expressed as total exposure per minute so that they could be used for comparison purposes (due to the prohibitive cost of running these simulations it was not possible to actually run the simulations for one full minute beyond when EB concentration was detectable). Tabulated exposure results calculated based on this methodology can be found in Table 5, which shows for each case, the extrapolated exposure per minute. The table also compares each case to the pre-covid scenario to demonstrate the reduction in exposure that is achieved by each intervention.

TABLES

Case #	Description	Front Door	Middle Door	Cab Window	Screen Gaps	Speech Holes
1	Pre-Covid19	Open	Closed	Closed	Large	Open
2	Initial Intervention: Seal speech holes	Open	Closed	Closed	Large	Sealed
3	Middle door boarding	Closed	Open	Closed	Large	Sealed
4	Middle door boarding and physical distancing (passenger standing 2m back)	Closed	Open	Closed	Large	Sealed
5	Middle door boarding and cab window open	Closed	Open	Open	Large	Sealed
6	Modified Screen Design – front door boarding	Open	Closed	Closed	Small	Sealed
7	Modified Screen Design – middle door boarding	Closed	Open	Closed	Small	Sealed
8	Modified Screen Design – both doors open for boarding and alighting	Open	Open	Closed	small	Sealed
9	Modified Screen Design – both doors open for boarding and alighting and cab window open	Open	Open	Open	Small	Sealed

Table 4. Cases investigated.

Case Number	Description	Exposure per minute (%), Percentage of exhaled/coughed concentration	Exposure per minute (%), Percentage of Pre-COVID-19 Case (S1)
1	Pre-Covid19	7.9	100
2	Initial Intervention: Seal speech holes	7.4	94
3	Middle door boarding	17.9	226
4	Middle door boarding and physical distancing (passenger standing 2m back, aerosols took longer to reach the driver's cab)	18	227
5	Middle door boarding and cab window open	0.02	0.3
6	Modified Screen Design – front door boarding	0.25	3
7	Modified Screen Design – middle door boarding	0.8	10
8	Modified Screen Design – both doors open for boarding and alighting	0.3	4
9	Modified Screen Design – both doors open for boarding and alighting and cab window open	0	0

Table 5 Tabulated exposure results

FIGURES

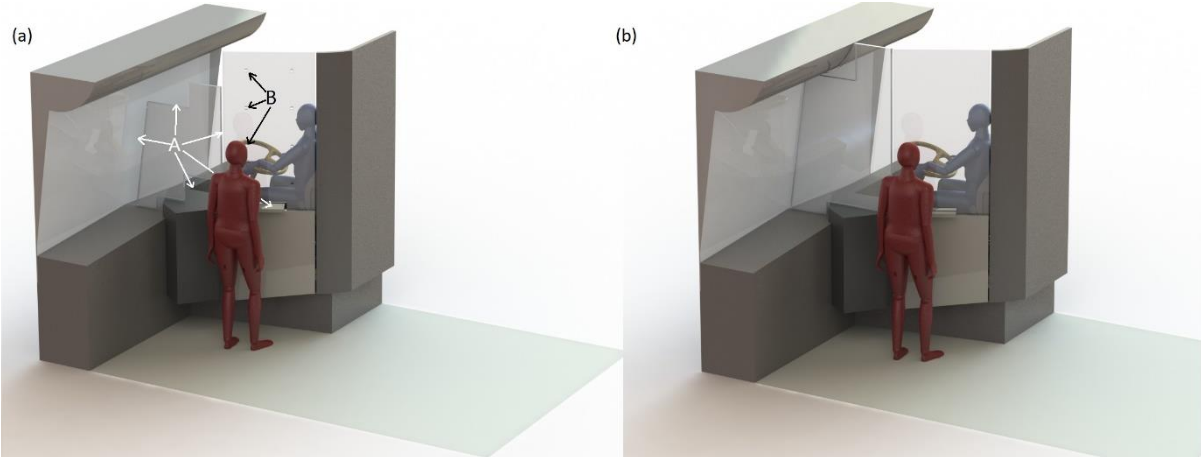

Figure 1: CAD-drawings of the passenger, driver and their cabin as imported into the Large-Eddy Simulation code depicting (a) Pre-covid-19 cab with large gaps and (b) modified assault screen with gaps between the saloon and the cab of maximum 5mm. Capital letters A and B point to gaps in the screen or speech holes, respectively.

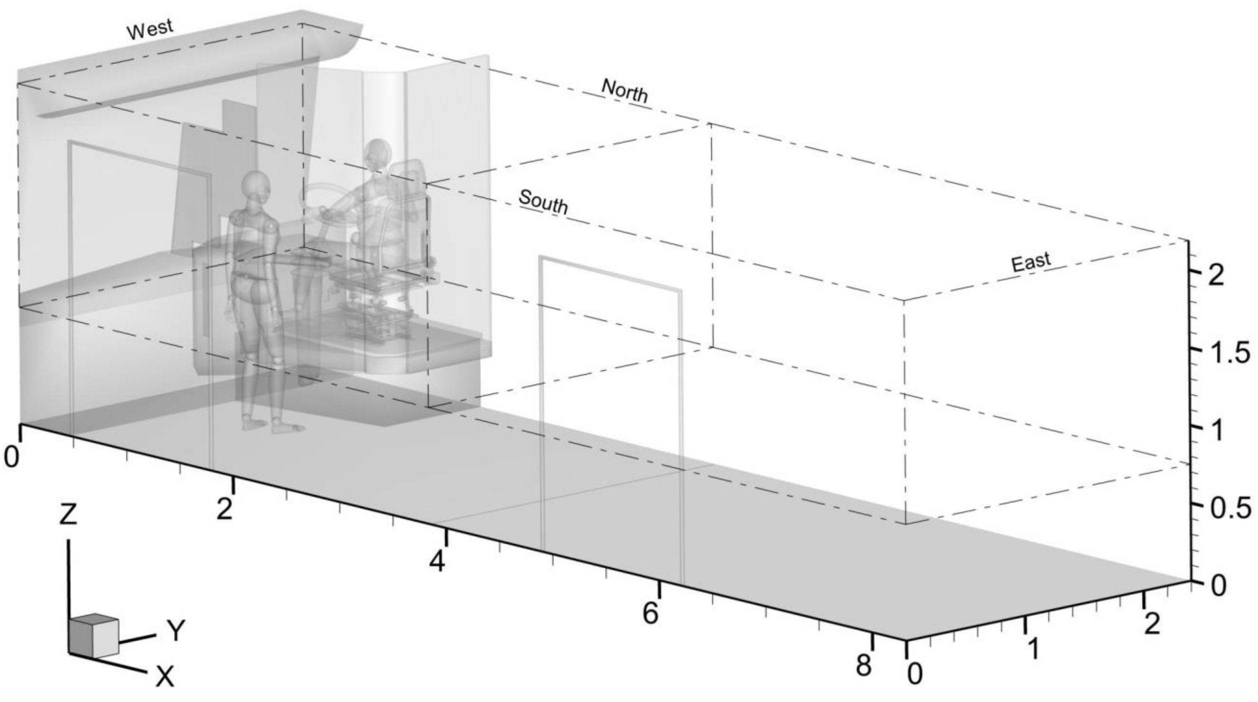

Figure 2: Simulation domain with boundaries.

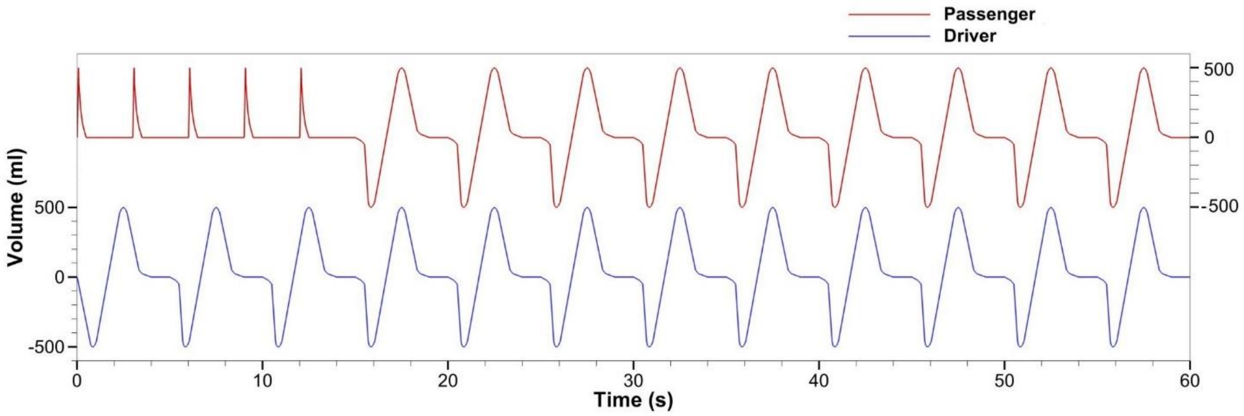

Figure 3: Breathing patterns for passenger (red) and driver (blue), both breathing in/out 500m/l of air per breath. The passenger coughs 5 times at the beginning of the simulation. The air exhaled is leaving the mouth at velocities ranging from 0m/s during the pause up to 8m/s during a cough.

Case S1: Pre-Covid19

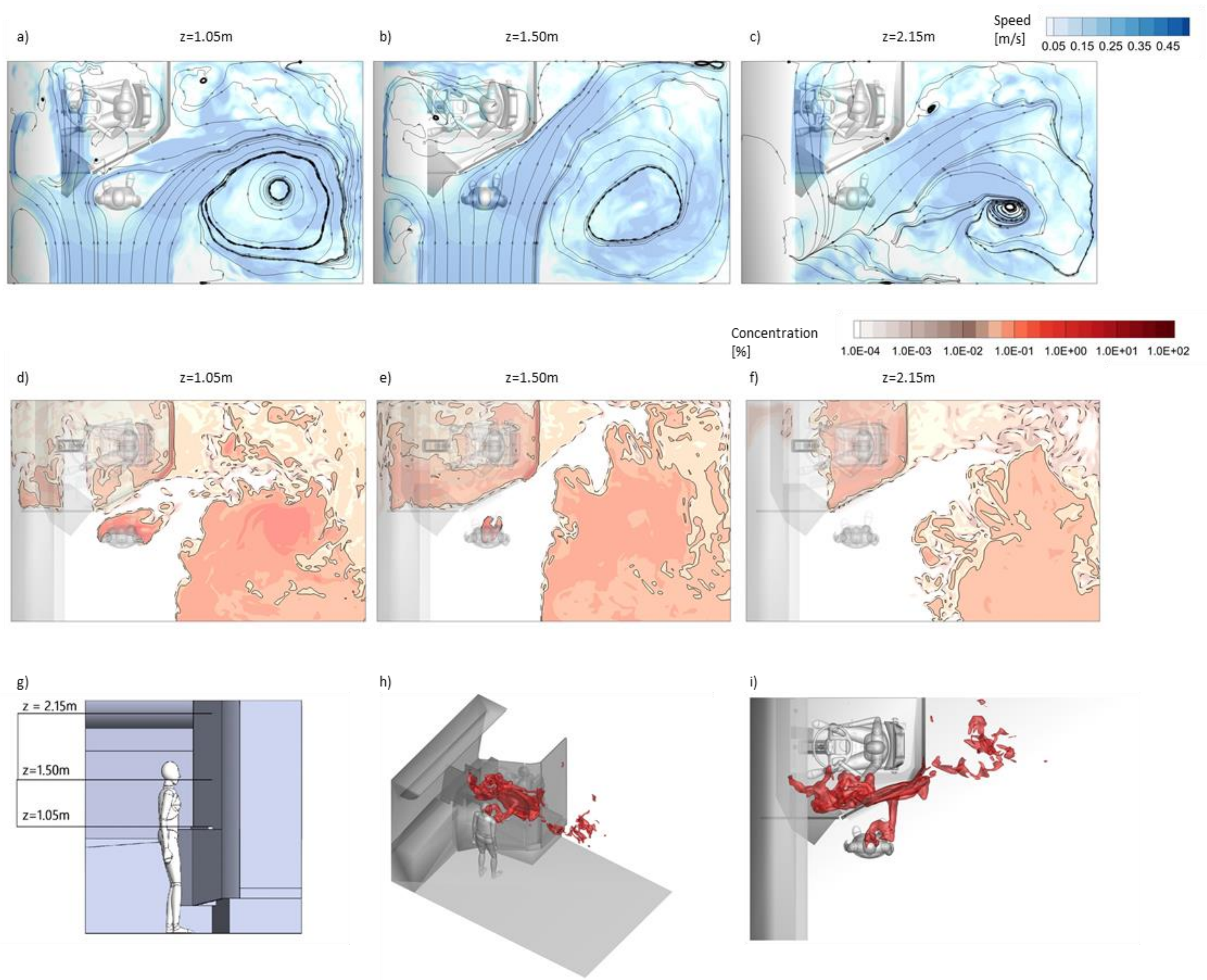

Figure 4: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S1 case: (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus. The front door of the bus is open, and air enters the bus from behind the passenger. Some air flows into the cabin via gaps in the assault screen (e.g. the ticket machine at z=1.05m) or along the windscreen (e.g. at z=1.50m) or through the opening in the screen for the rear-view mirror (at z=2.05m). Most of the air is deflected by the cabin towards the rear of the bus. (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S1 case: (d) at a height just above the waist, (e) at the height of the passenger's mouth, (f) near the roof of the bus. Aerosols have entered the cab and remain in the cab and concentration levels are quite high regardless of the height. Aerosol concentration in the cabin reach approximately 10% of the original concentration coming out of the passenger's mouth (i.e. 100%). (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after 13s of real time of the S1 case from two different viewpoints: (h) oblique view from behind and (i) view from above. Many small aerosols (or aerosols) enter the cabin after the coughing episode via the speech holes and gaps around the assault screen (i) whilst others are being barred from entering by the screen (h) or are transported by the flow towards the rear.

Case S2: Initial Intervention: Seal speech holes

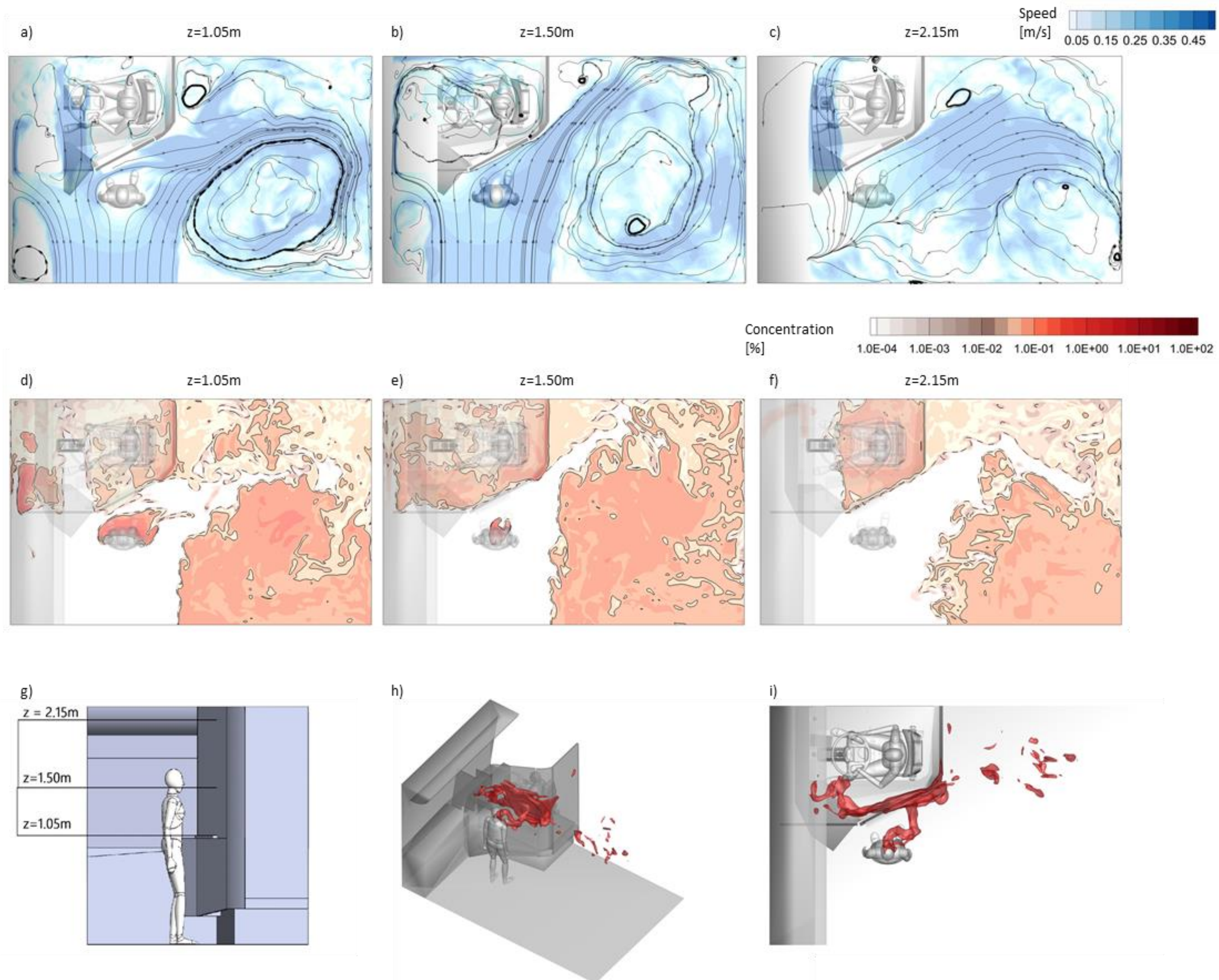

Figure 5: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S2 case: (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus. The front door of the bus is open, and air enters the bus from behind the passenger. Some air flows into the cabin via gaps in the assault screen very similar to the S1 case. (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S2 case: (d) at an elevation just above the waist, (e) at the elevation of the passenger's mouth, (f) near the roof of the bus. Aerosols have entered the cab via the larger gaps in the assault screen and remain in the cab and concentration levels at 60s are very similar to the S1 case. (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after 13s of real time of the S2 case from two different viewpoints: (h) oblique view from behind and (i) view from above. Many small aerosols (or aerosols) enter the cabin after the coughing episode via the gaps around the assault screen (i) whilst others are being barred from entering by the screen (h) or are transported by the flow towards the rear.

Case S3: Middle door boarding

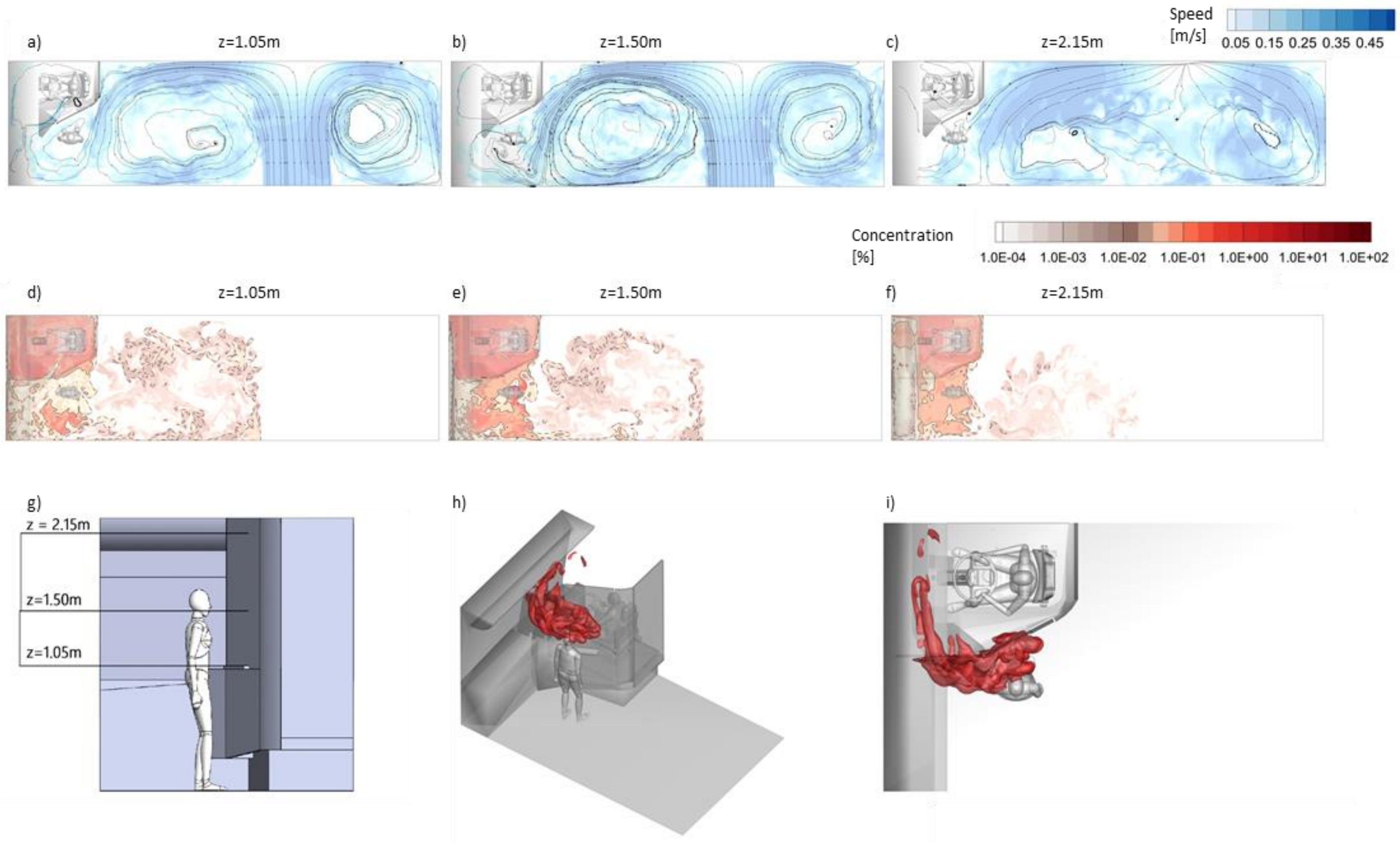

Figure 6: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S3 case, i.e. only the mid door is open for boarding: (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus. The mid door of the bus is open, and air enters the bus from the right of the passenger. The airflow is split into two streams at the lateral boundary of the bus and two large recirculation regions appear. Some air flows towards the front of the bus around the passenger and preferentially along the windscreen and via the opening of the ticket machine into the driver's cabin. This is mainly taking place at the two lower elevations (a) and (b) whereas the air below the roof is more or less driven by the recirculation at lower elevations. (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S3 case. (d) at a height just above the waist, (e) at the height of the passenger's mouth, (f) near the roof of the bus. Aerosols have entered the cab mainly via the larger gaps in the assault screen and remain in the cab, concentration levels at 60s are very high with peak concentrations in the cab reach 60% of the aerosols that come out of the passenger's mouth. With middle door open only, the air flow keeps the aerosols in the front of the bus and over time a great percentage of them end up in the cabin. (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after the full (five times) coughing episode (13s) of real time of the S3 case from two different viewpoints: (h) oblique view from behind and (i) view from above. Aerosols enter the cabin via the rear-view mirror gap in the assault screen.

Case S4: Middle door boarding and physical distancing (passenger standing 2m back)

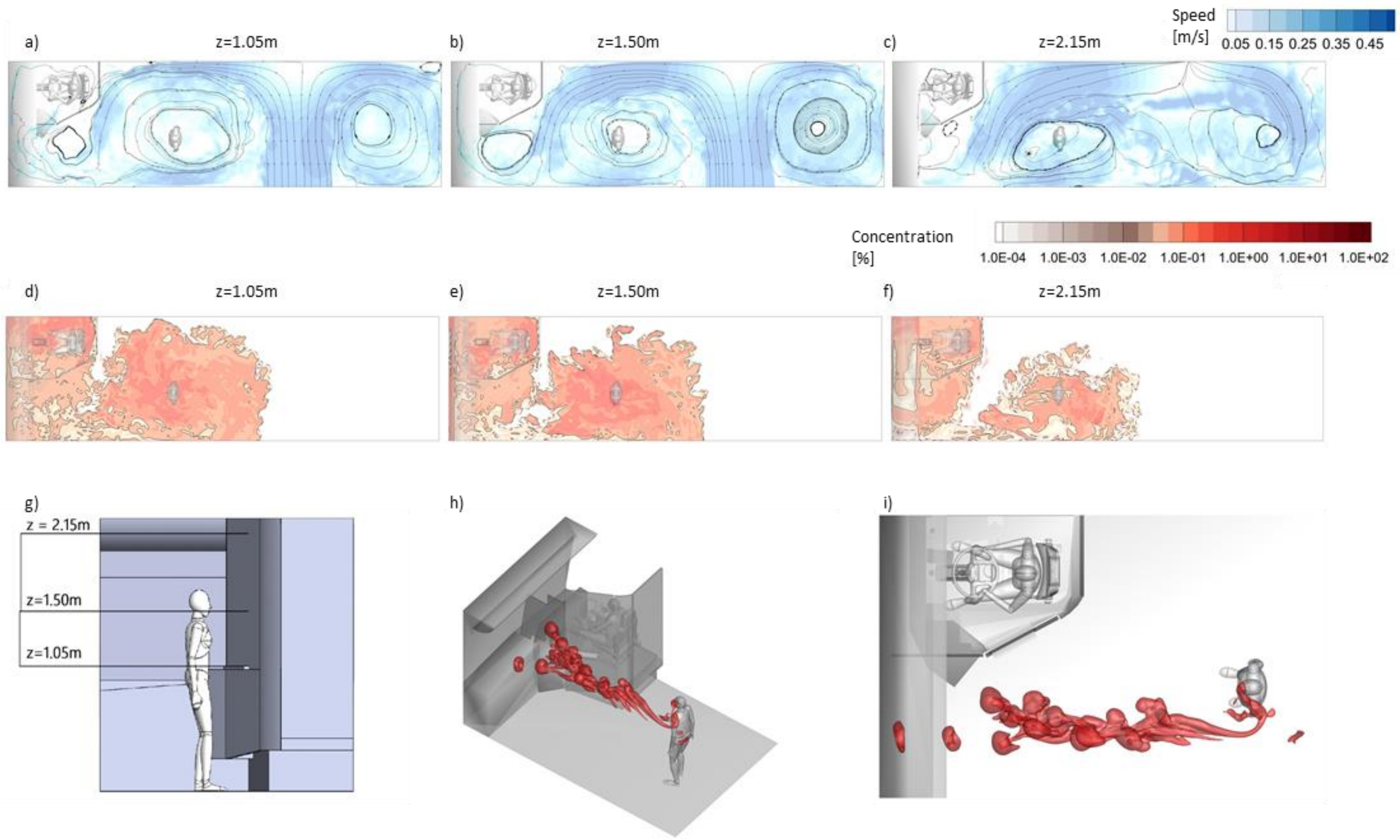

Figure 7: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S4 case, i.e. only the mid door is open for boarding and the passenger stands 2m away from the assault screen. (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus and (d) sketches the elevation of these planes and provides the concentration contour legend. The mid door of the bus is open, and air enters the bus from the right of the passenger. The airflow is very similar to the S3 case. (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S4 case. (d) at an elevation just above the waist, (e) at the elevation of the passenger's mouth, (f) near the roof of the bus. Analogous to the S3 case, aerosols have entered the cab mainly via the larger gaps in the assault screen and remain in the cab and concentration levels at 60s are quite high and peak concentrations in the cab reach 60% of the aerosols that come out of the passenger's mouth. With middle door open only, the air transports the aerosols towards the front of the bus and over time a great percentage of them end up in the cabin. The location at which the passenger releases the aerosols is insignificant. (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after the coughing episode (13s real time) of the S4 case from two different viewpoints: (h) oblique view from behind and (i) view from above. Aerosols are carried towards the front of the bus but are yet to enter the cabin area. The balloons in concentration highlight the coughing episodes of the passenger.

Case S5: Middle door boarding and cab window open

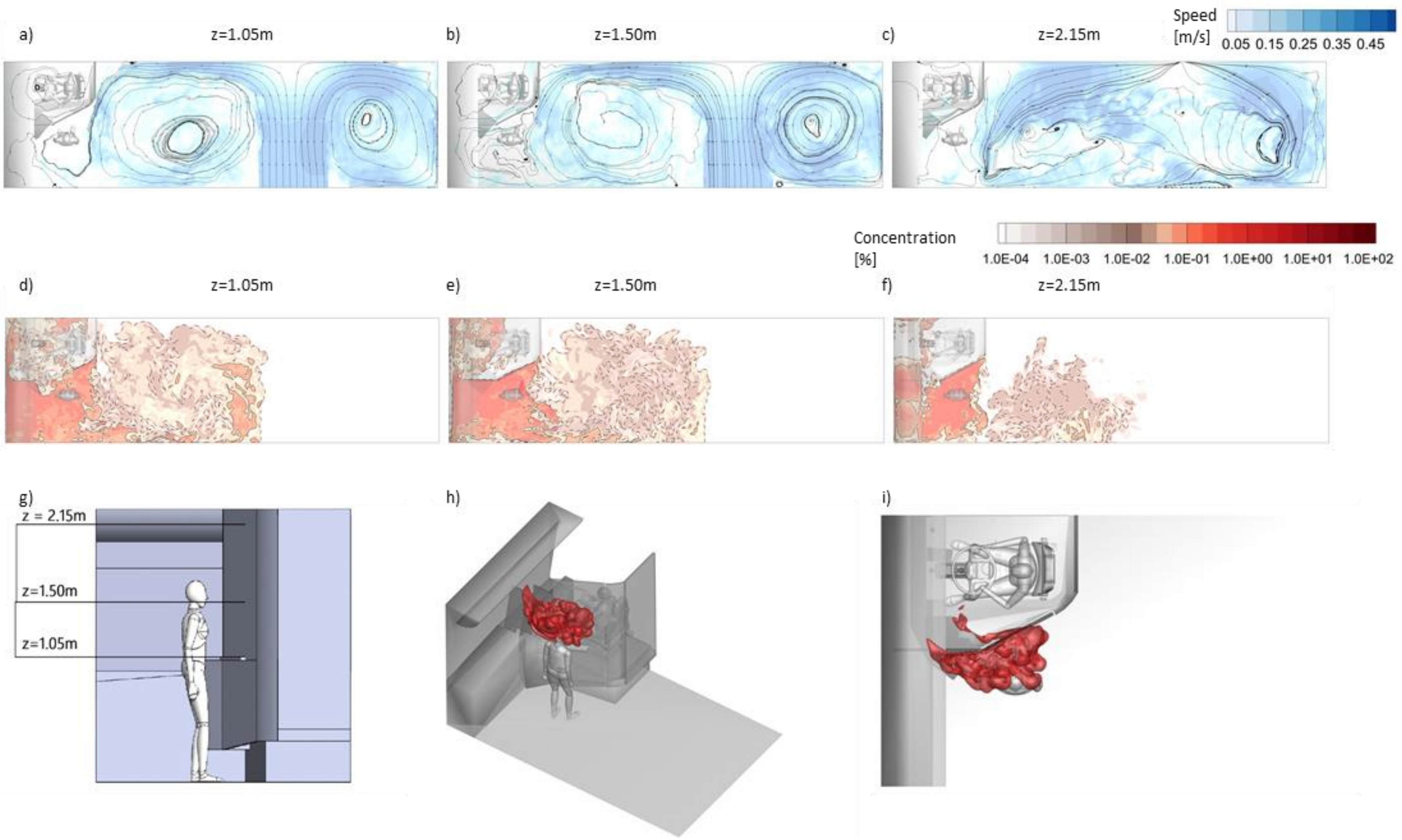

Figure 8: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S5 case, i.e. only the mid door is open for boarding but here with the cabin window open. (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus and (d) sketches the elevation of these planes and provides the concentration contour legend. The mid door of the bus is open, and air enters the bus from the right of the passenger. The airflow is very similar to the S3 case except for in the driver's cabin. The recirculation of air above the steering wheel draws in air through the window and ventilates the cabin. This is particularly visible at the elevation of the driver's head (b). (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S5 case. (d) at a height just above the waist, (e) at the height of the passenger's mouth, (f) near the roof of the bus. Fewer aerosols than in the S3 and S4 cases have entered the cabin and concentration levels at 60s are lower than for these two cases, in particular around the driver, which is due to the additional mixing and dissolution of the aerosols by incoming air. Also, as a result of air flowing into the cab through the open window the few aerosols that have entered are kept away from the driver. This is particularly noticeable at heights z=1.50m (b) and z=2.15m (c). (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after the coughing episode (13s real time) of the S5 case from two different viewpoints: (h) oblique view from behind and (i) view from above. Aerosols enter the cabin via the rear-view mirror gap in the assault screen and the gap between the door and the assault screen.

Case S6: Modified Screen Design – front door boarding

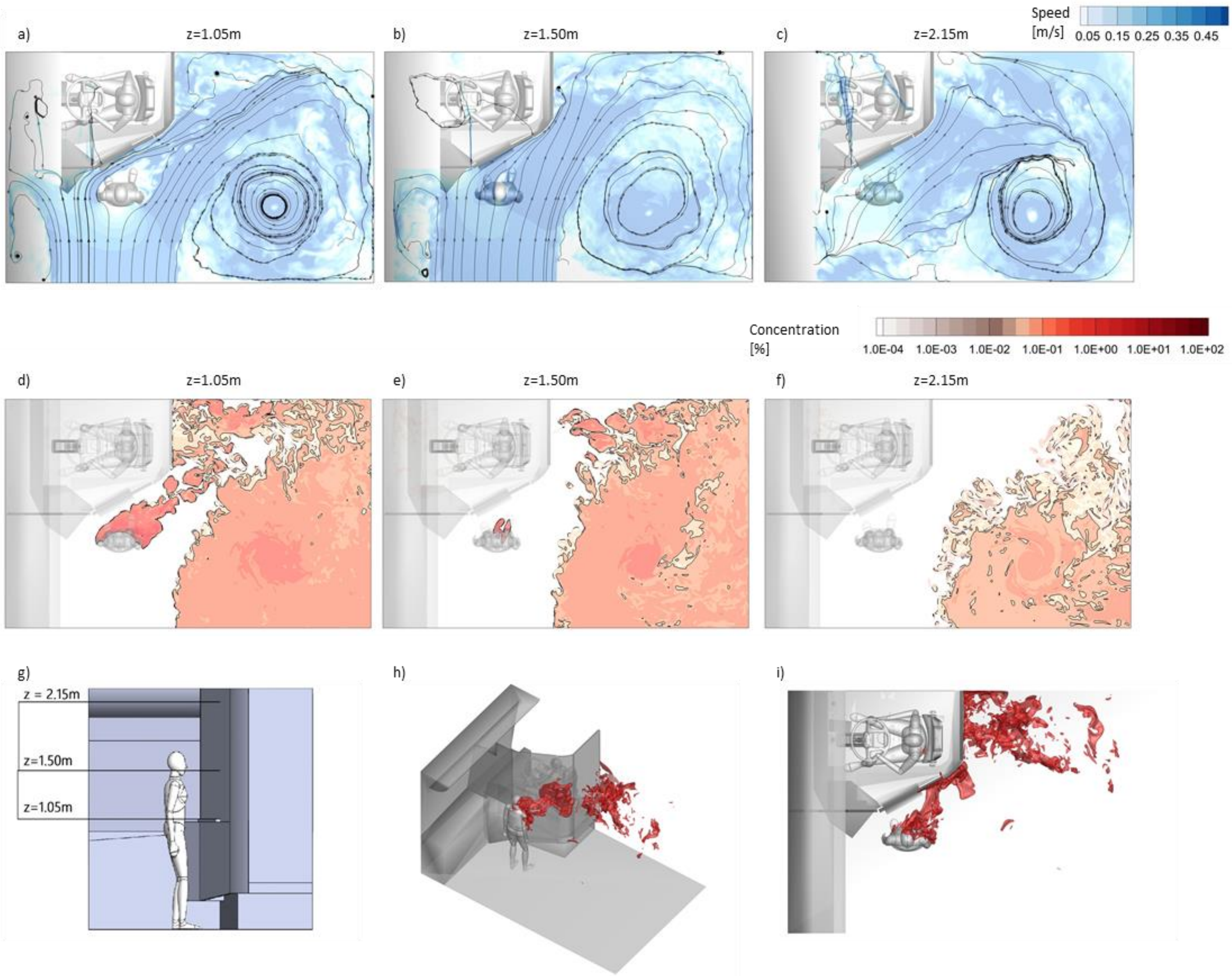

Figure 9: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S6 case, i.e. front door is open only and the screen has been modified by closing the gaps to a maximum of 5mm. (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus and (d) sketches the elevation of these planes and provides the concentration contour legend. The both doors are open, and air enters the bus. As with the S1 and S2 cases the open front door results in airflow in the front of the bus and preferentially away from the cabin. Only a very little amount of air can enter the modified cabin because the gaps are very small. (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S6 case. (d) at an elevation just above the waist, (e) at the elevation of the passenger's mouth, (f) near the roof of the bus. Reducing the gaps in the assault screen has a marked effect, hardly any aerosols have been transported into the cabin at 60s. (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after the coughing episode (13s real time) of the S6 case from two different viewpoints: (h) oblique view from behind and (i) view from above. Aerosols still enter the cabin through the small gaps between the door and its frame, however, most of the aerosols are carried further into the bus, away from the driver's cabin.

Case S7: Modified Screen Design – middle door boarding

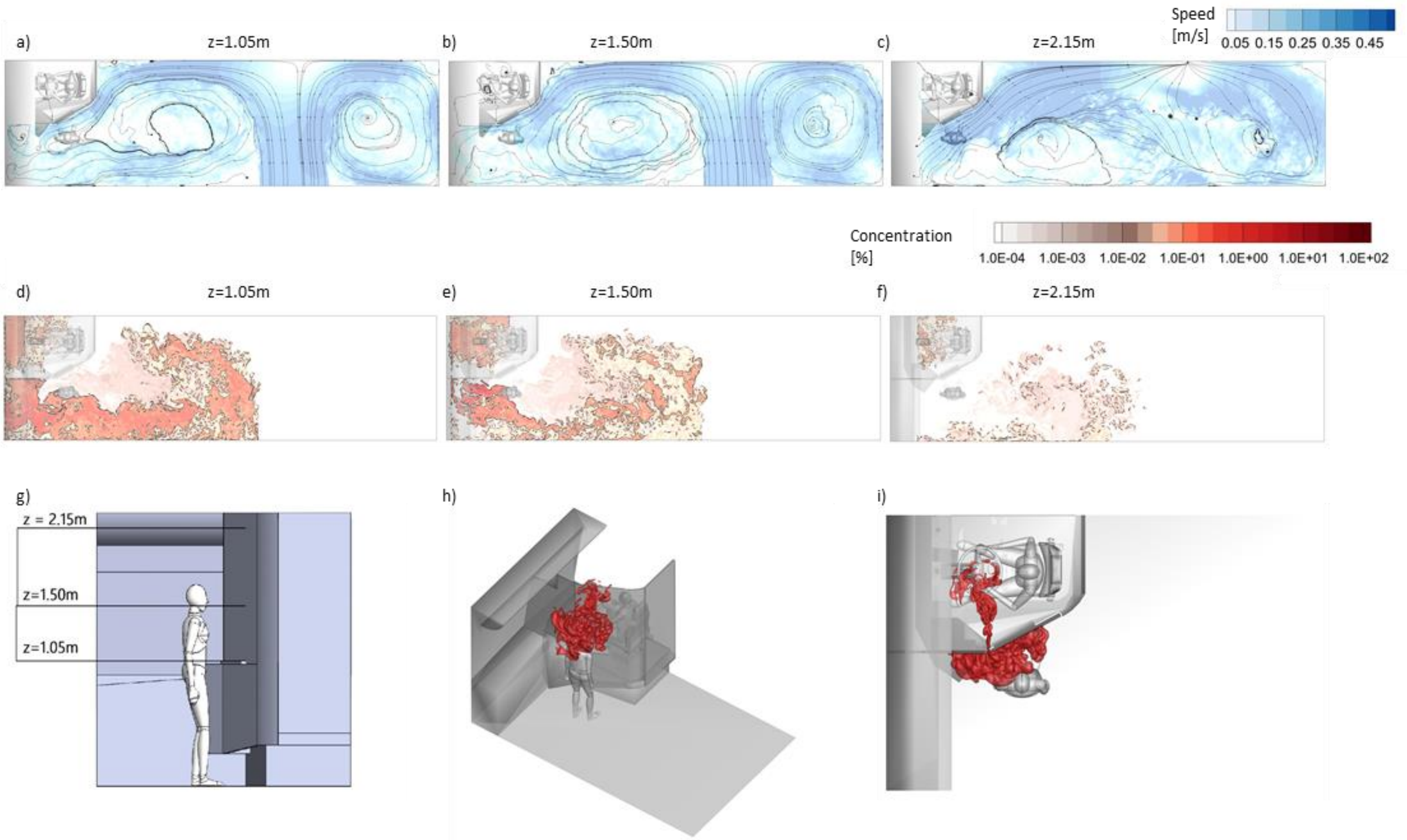

Figure 10: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S7 case, i.e. only the middle door is open, and the assault screen modified. (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus and (d) sketches the elevation of these planes and provides the concentration contour legend. Flow patterns are similar to the S3, S4 and S5 cases with airflows towards the front of the bus. Due to the modified screen only a small amount of air can enter the modified cabin because the gaps are very small. (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S7 case. (d) at an elevation just above the waist, (e) at the elevation of the passenger's mouth, (f) near the roof of the bus. Reducing the gaps in the assault screen has reduced the number of aerosols in the cab however at z=1.05m there are quite a large number of aerosols in the cab. This is because the aerosols can enter the cab at the bottom even through very small gaps during the coughing episode. This is highlighted in (i). The concentrations are very small and the exposure at the driver's mouth was found to be small, but these figures show that middle door boarding only is less advisable. (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after the coughing episode (13s real time) of the S7 case from two different viewpoints: (h) oblique view from behind and (i) view from above. Aerosols enter the cab via the very small gap between the cabin door and the rest of the cabin, as it is being pushed in by the airflow coming from the middle door towards the front.

Case S8: Modified Screen Design – both doors open for boarding and alighting

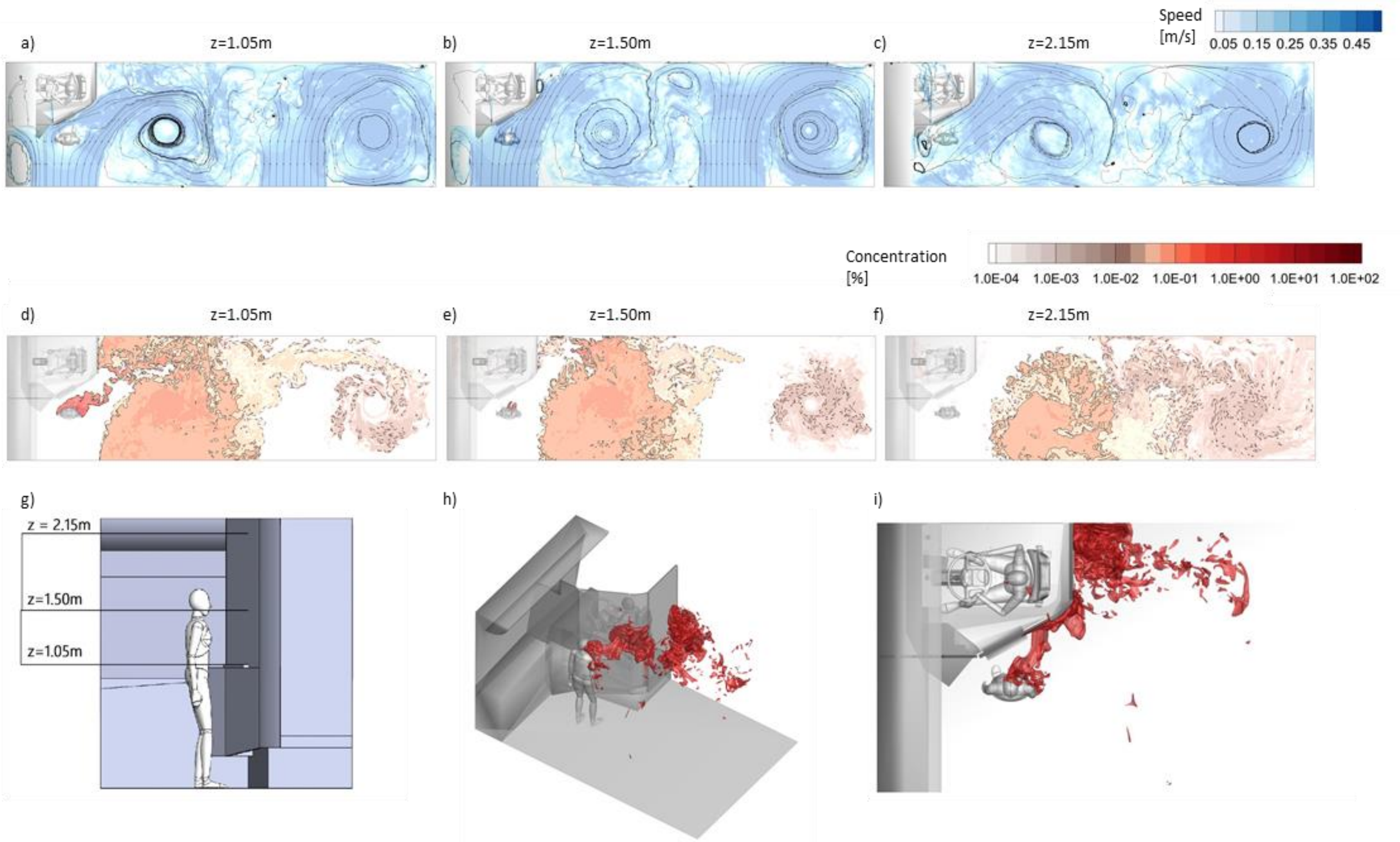

Figure 11: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S8 case, i.e. both doors are open for boarding and alighting. (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus and (d) sketches the elevation of these planes and provides the concentration contour legend. The both doors are open, and air enters the bus. Two two large recirculation regions appear similar to the S3/S4/S5 cases however the open front door results in airflow in the front of the bus is preferentially away from the cabin. Only very little amount of air can enter the modified cabin because the gaps are very small. This is mainly taking place at the two lower elevations (a) and (b) whereas the air below the roof is more or less driven by the recirculation at lower elevations. (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S8 case. (d) at an elevation just above the waist, (e) at the elevation of the passenger's mouth, (f) near the roof of the bus. Reducing the gaps in the assault screen and airflow through the front door has resulted in hardly any aerosols in the cab. (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after the coughing episode (13s real time) of the S8 case from two different viewpoints: (h) oblique view from behind and (i) view from above. Very few aerosols still enter the cabin through the small gaps between the door and its frame; most are carried further into the bus, away from the driver's cabin.

Case S9: Modified Screen Design – both doors open for boarding and alighting and cab window open

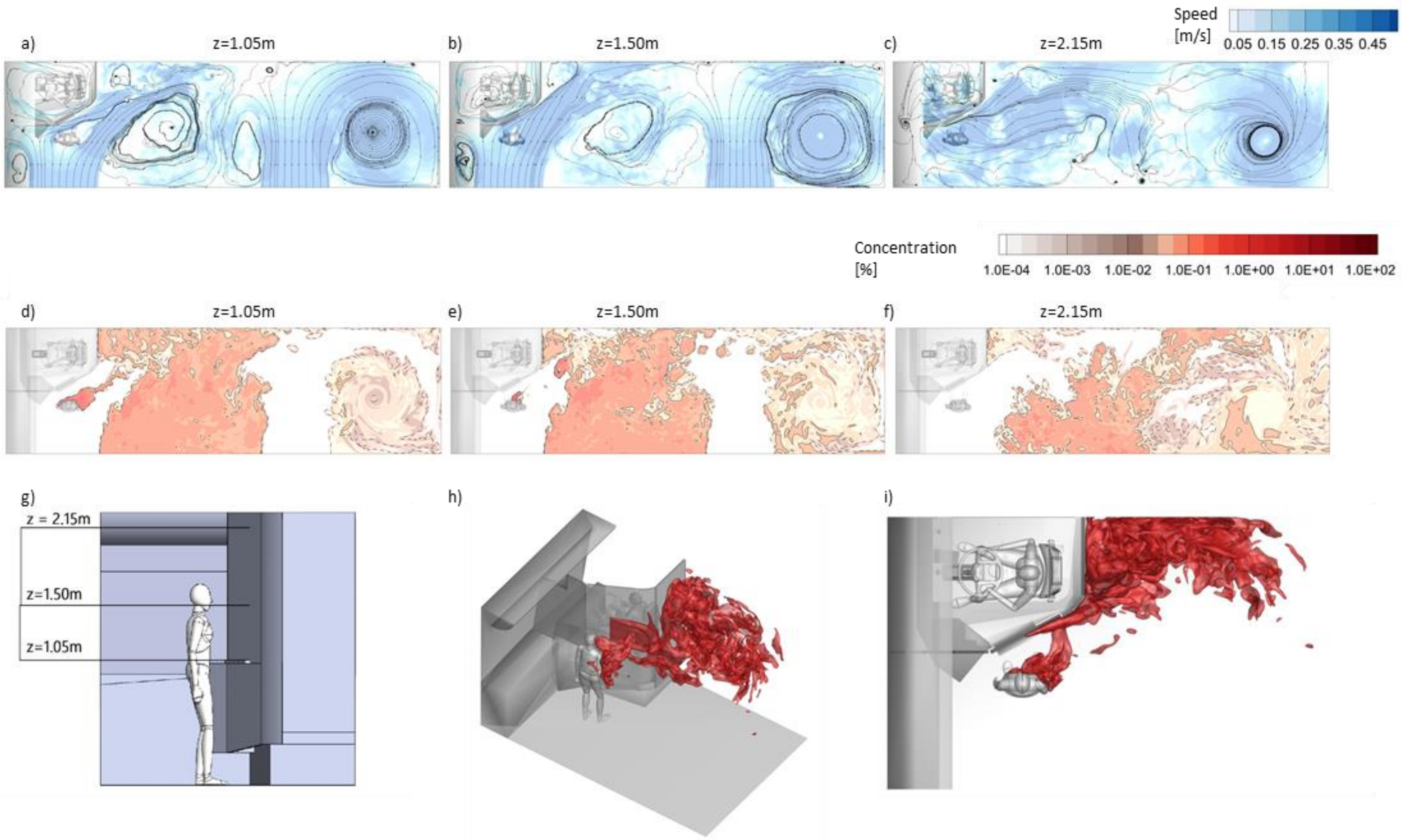

Figure 12: (a-c) Streamlines of the airflow and contours of the velocity magnitude in three selected horizontal planes at t=60s of the S9 case, i.e. both doors are open for boarding and alighting and the driver's cab window is open. (a) at an elevation just above the waist, (b) at the elevation of the passenger's mouth, (c) near the roof of the bus and (d) sketches the elevation of these planes and provides the concentration contour legend. The airflow in the bus are very similar to the S8 case except inside the driver's cabin into which air enters through the window and air circulates around the driver. Almost no air can enter the modified cabin because of that circulation, except for near the bus roof. (d-f) Contours of the aerosol concentration in logarithmic scale in three selected horizontal planes approximately at t=60s of the S9 case. (d) at an elevation just above the waist, (e) at the elevation of the passenger's mouth, (f) near the roof of the bus. Because air flows into the cabin from the saloon only near the roof, no aerosols are dispersed into the cabin. (g) sketches the elevation of the planes used in (a-f). (h-i) Isosurfaces of 1% concentration of the passenger's exhaled aerosols after the coughing episode (13s real time) of the S9 case from two different viewpoints: (h) oblique view from behind and (i) view from above. The aerosols are carried into the saloon away from the driver's cabin and do not propagate into the cabin area due to the assault screen modification and the ventilation provided by the open cabin window.

All Cases compared

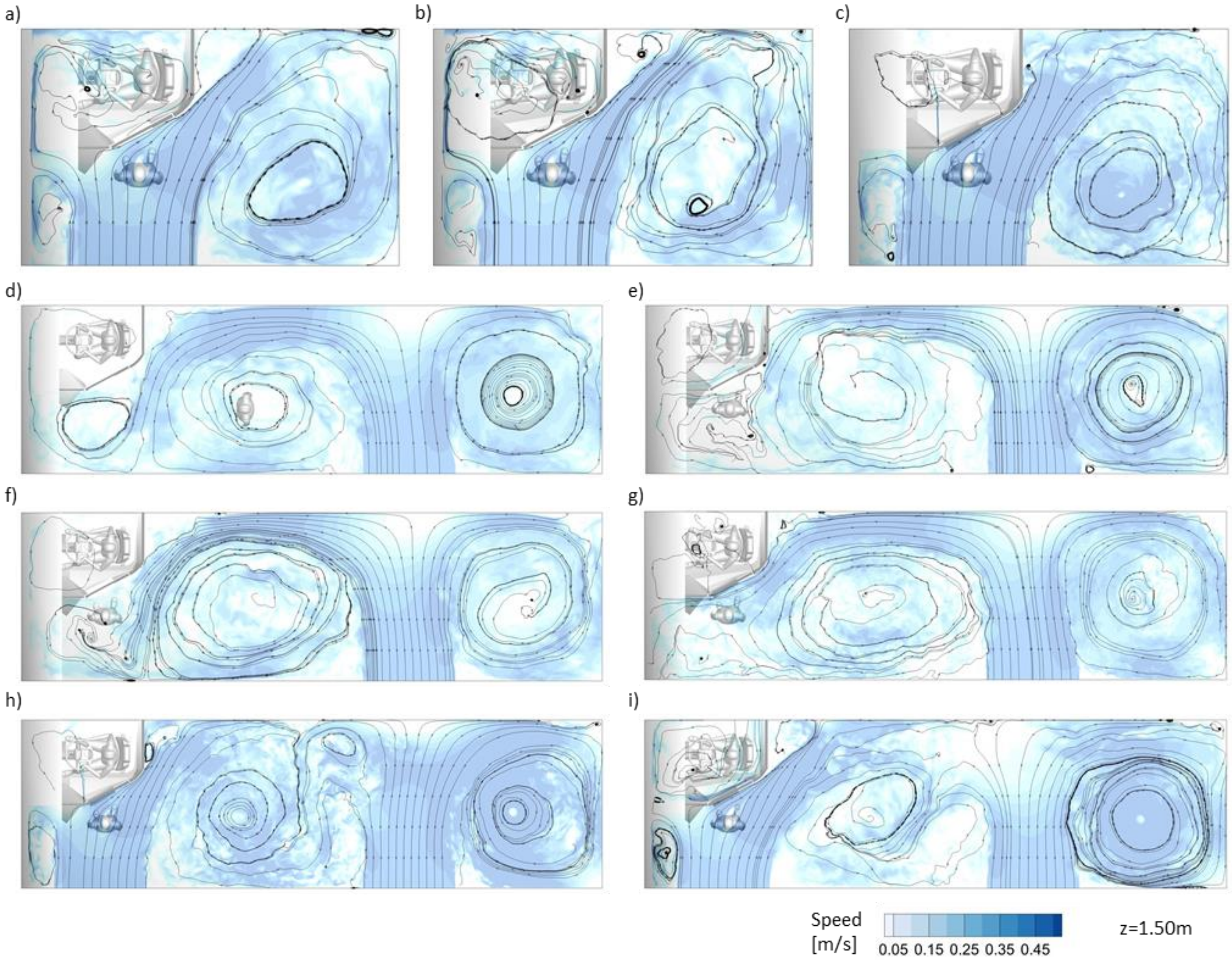

Figure 13: Velocity Magnitude Comparison Panel: Velocity magnitude plots and streamlines at z=1.50m for all cases, in a clockwise direction starting at the top left-hand corner, a) S1, b) S2, c) S6, d) S4, e) S5, f) S3, g) S7, h) S8, i) S9.

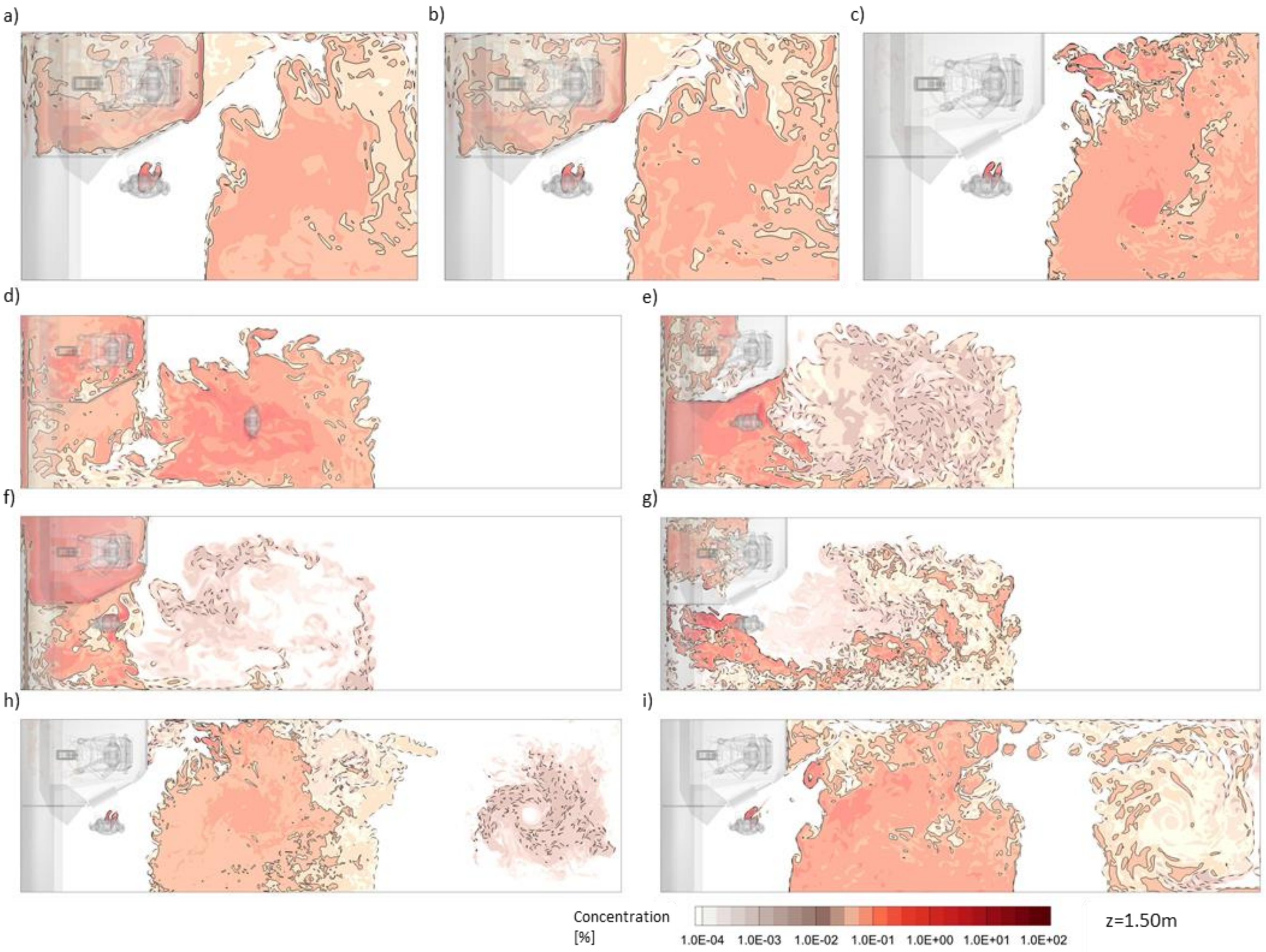

Figure 14: Scalar Comparison Panel: Scalar concentration plots at z=1.50m for all cases, in a clockwise direction starting at the top left-hand corner, a) S1, b) S2, c) S6, d) S4, e) S5, f) S3, g) S7, h) S8, i) S9.

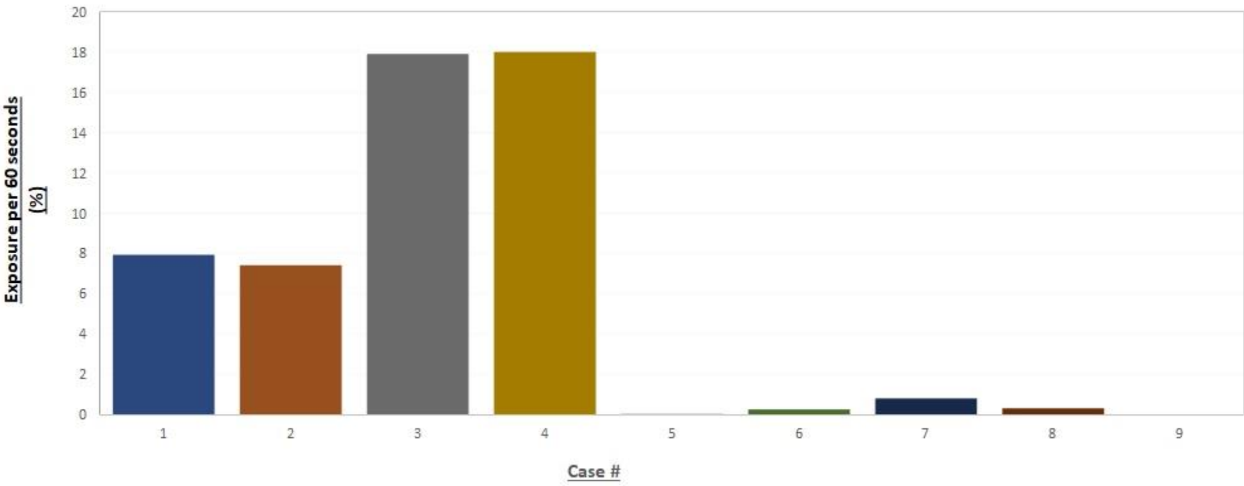

Figure 15: Total exposure to EB per minute (%) for all cases; EB concentration results taken within the cabin area 5 cm in front of the driver's mouth

Appendix B

Submitted to Sage Environmental Modelling Group

Clean indoor air in the COVID-19 pandemic: the case for improving ventilation standards

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Executive Summary

The UK entered a 'lockdown' on the 23rd of March, to slow the spread of infections with COVID-19. Lockdown measures have mainly relied on complete social distancing amongst co-workers, schools, families and social networks. These were extremely effective in reducing infection rates, at enormous economic and social cost.

Currently, Public Health England does not consider airborne transmission of the disease to be a primary risk factor. Its guidance states "*The transmission of COVID-19 is thought to occur mainly through respiratory droplets generated by coughing and sneezing, and through contact with contaminated surfaces. The predominant modes of transmission are assumed to be droplet and contact*"[i], and the primary advice given to the public is to keep a 2-metre distance. The guidance refers to the possibility of aerosolization only in certain clinical contexts (e.g. Aerosol Generating Procedures). The guidance also refers to ventilation, stating that "T*he rate of clearance of aerosols in an enclosed space is dependent on the extent of any mechanical or natural ventilation – the greater the number of air changes per hour (ventilation rate), the sooner any aerosol will be cleared*", and providing targets for hospital air change rates, yet does not go further to recommend high ventilation rates in other settings.

A rapid expert consultation response to the US National Academies of Sciences, Engineering and Medicine was published on April 1st, 2020. The authors concluded that "While the current SARS-CoV-2 specific research is limited, the results of available studies are consistent with aerosolization of virus from normal breathing"[ii]. They also note that precise values for the proportion of infections due to air droplet, aerosol or fomite transmission do not exist for any respiratory virus. Since then new evidence has been accumulating. The virus has been shown to remain viable in aerosols in the air for at least 3 hours[iii]. Under the assumption that the virus is not airborne, to date no interventions have been made in the UK to improve indoor ventilation, which is a recognised route to reduce risk of infection in airborne infectious diseases.

The following brief report aims to gather evidence from multi-disciplinary sources to investigate the possibility that the airborne route of the transmission for COVID-19 may explain, at least partly, the high transmission rates of the disease. The evidence considered includes also design guidelines for ventilation in the UK and in some other countries, and the report demonstrates a range of real-life situations and applications that may have caused a higher risk of transmission indoors, even when infected carriers did not appear symptomatic. We also present some research findings from our group on one particular indoor environment; investigating the safety of bus drivers, by modelling a passenger coughing in front of the assault screen on a standard London bus. Our simulations demonstrated that after the initial spray of larger droplets settled on surfaces and on the floor, smaller aerosols remained suspended in the air and were transported into the driver's cabin where they were breathed in by the driver.

This report makes the case that urgent but simple interventions could be implemented in terms of utilizing high ventilation rates and fresh air to reduce rates of infection in indoor public spaces. We recommend that further research and more comprehensive guidelines and risk assessments must be established before the colder weather in the Autumn 2020 due to the seasonal impact on HVAC systems and as a second wave of infections is anticipated to occur, coinciding also with the annual winter influenza outbreaks.

As the lockdown now begins to lift, there is a pressing need to redesign and reconfigure public spaces in a way that is evidence-based, and allows meaningful social interactions with minimal risk of exposure to SARS-CoV-2 and other, potential infectious diseases in the future. This too will require a huge collective effort. As the evidence that the virus might be airborne is mounting, we may not yet, or ever, know the precise dose rate for an infection, but it seems timely to adopt a common-sense approach towards reducing the risks of its transmission sooner rather than later.

It is vital that this new order considers all evidence around possible routes of transmission of the disease, so that these sacrifices are impactful and can be maintained at the appropriate level in and by the public domain for as long as possible. Most importantly, that sacrifices are not ultimately seen to have been made in vain.

Routes of Infection

1. Nowhere has the attack rate of infections with COVID-19 been more striking than in London, where it is estimated by the MRC Biostatistics unit and PHE that between 16-26%of the London population have been infected. At its peak on the 23rd March, they estimate that up to 268,000 Londoners had been newly infected in a single day. London's population is similar to that of some small countries that had infection rates and numbers of orders of magnitude lower than that. Londoners rely on an overcrowded transport system, very high occupancy rates in office buildings, crowded restaurants and shopping districts and even streets; often with poor ventilation. The large number of infected carriers in these settings suggest that ventilation must be considered important in the public sphere, not only in hospitals.
2. It is widely accepted that the main route of infection in COVID-19 is through contact with contaminated surfaces, and exposure to larger droplets produced by coughs and sneezes. But there is a growing body of evidence that there can be additional transmission through airborne aerosols, especially in closed indoor environments. This has not yet been conclusively proven by direct experimentation. However, the rate of infection reported in London, *despite using lockdown measures to stop infections*, is at least as high as the typical rates of infection of Influenza in the unvaccinated population, reported to be 18% of unvaccinated people in the UK each winter on average, for the years 2006-2010[iv].
3. Influenza is understood to be airborne and to be very easily transmissible by breathing the air in crowded places; a recent study detected influenza virus directly in air samples in a primary school and quantified the virus, concluding that the virus was present in doses high enough to cause infection[v]. During the SARS epidemic of 2003, possible airborne transmission of SARS-CoV-1 was suspected in some super-spreading events such as in a hospital in Canada and the Amoy Gardens in Hong Kong. It was also found to be transmitted on an aircraft, in which more than 90% of infections occurred in passengers seated more than 1 m away from the patient, two occurred up to 7 rows away. Airborne small aerosol particles rather than large droplets were identified as the likely explanation[vi].
4. A recent study found SARS-CoV-2 to be viable in suspended aerosols for at least 3 hours[8]and concluded that aerosol transmission is plausible. A report released last week[vii], investigating infection and transmission of this virus between ferrets, concluded the possibility of airborne transmission to the ferrets that had not had direct contact with the infected individuals.
5. Anecdotal evidence is emerging of high rates of attack for SARS-CoV-2 originating from asymptomatic infected individuals in crowded indoor environments, coupled with poor ventilation or air conditioning systems set to recirculation mode. These include a restaurant in Guangzhou[viii], and an analysis of two outbreaks in Zhejiang, China, one linked to infected people travelling on two buses to a temple and the other at a training workshop in a conference room[ix]. Super-spreading events have been widely publicised by the media. Notable are cases where singing or religious prayers took place, such as the case of a choir practice in Washington state, USA[x]; the first large cluster identified in the US, which centred around over 100 infections at a synagogue in New York state[xi]; and the case of the South Korean Shincheonji church where a single woman infected dozens of worshippers who had been crowding and praying for long hours in an unventilated space[xii]. Physiological processes such as breathing, talking, and coughing do produce very small aerosols as well as larger droplets, in varying concentrations. Sustained vocalization was found to produce higher concentrations of small aerosols than regular talking or breathing[xiii].
6. The initial dose of virus was found to be a factor in the high mortality of the second and third waves of the 1918-1919 Spanish flu epidemic[xiv] and might also worsen the severity of COVID-19 disease[xv], which to date has produced one wave of infection. Despite the use of PPE, many healthcare workers are sadly developing severe illness and dying and it is suspected that the severity of their illness, in some cases at a young age and with no underlying conditions, is due to the initial exposure to high doses of the virus. Large numbers of asymptomatic carriers may be unwittingly exposing essential workers such as bus, coach and taxi drivers, and people working in retail, leisure and other service occupations. These groups have also been identified as having had the highest rates of death, especially for men[xvi].

The Role of Ventilation

7. The crucial role of ventilation gained special recognition during the SARS epidemic of 2003, when an outbreak at The Prince of Wales Hospital in Hong Kong was linked to an inefficient ventilation system. The SARS epidemic, along with MERS, H1N1 influenza, and the possibility of bio-terrorism all have been identified as potentially serious threats in public spaces. Investigations of indoor ventilation systems identified them as effective strategies to lower infections for SARS and influenza in a wide variety of settings outside hospitals[xvii]. To date, high rates of ventilation to flush out contamination remain the only identified mitigation measure. Since then, further research into airborne biological contaminants is being carried out in South East Asia, for example, in Seoul high bacteria levels were found in underground stations with poor ventilation compared with well-ventilated stations[xviii]. In Taiwan's Taipei Metro system, bacterial concentrations were also found to be higher than their regulations allow for[xix].

8. Most air quality (AQ) guidelines in the UK and in Europe use CO_2 as a proxy for good AQ and do not refer specifically to bacterial counts, viruses or fungi. However, in 2004, perhaps due to lessons learnt from the 2003 SARS outbreak, 'Indoor Air Quality (IAQ) Control in Public-use Facilities, etc. Act/Korea' was amended to control IAQ in public facilities, including underground subway stations, underground shopping malls, medical institutions, large shops, movie theatres and newly-built multiunit housing. These must now comply with AQ limits on indoor pollutants such as PM10, carbon dioxide CO_2, formaldehyde, and carbon monoxide CO, as well as total airborne bacteria[xx]. IAQ guidelines for public transport have also been enforced since 2014. Guidelines on indoor air quality in Singapore from 1996 also include recommended limits for fungal and bacterial counts[xxi]. Besides the standards mentioned above in Taiwan, Singapore and South Korea, guidance published in Hong Kong in 2003 introduced recommended standards on IAQ of public transportation and described in detail how to achieve these, leading also to IAQ monitoring efforts on their systems[xxii].
9. Use of healthcare-grade PPE is not currently feasible for the general public or even for people who work in public facing jobs outside of healthcare settings, but the public sphere currently offers no protection measures to reduce infection, leading to loss of public trust. Hospital settings in the UK have strict guidelines aiming for high ventilation rates, at which all the air in a room has been replaced with fresh air, which can be up to 12 times higher than those required in commercial buildings or schools. As we do not know what the infectious dose is for this virus, better ventilation should be routine also in all public settings.
10. Unfortunately, poor IAQ is endemic in the UK following many years where energy-saving has dominated the built environment agenda, at the expense of health and wellbeing. The design of airtight spaces where ventilation and air conditioning systems are set to recirculate stale air instead of bringing fresh air is now understood to be poor design that is putting our health at risk. Sustainable development is vitally important to our future, and needs to be achieved in novel and creative ways, balancing our health requirements and accounting for more sophisticated measures of indoor air quality.

An assessment of airflow, ventilation, virus and risk mitigation

Our team from UCL involving environmental, fluid, microbial and transport engineers is working on research using Computational Fluid Dynamics. Computer simulations were performed by the Engineering Fluid Mechanics group on its in-house Large-Eddy Simulation code that has been verified for a large number of flows. As a multi-scale problem solved at very high temporal and spatial resolution, these simulations were run on a supercomputer to get flow velocities and concentrations for aerosol droplets. We tested a typical scenario on a bus, including people and patterns of breathing and coughing. This work, presented in the Appendix, is ongoing but it demonstrates how very small respiratory aerosols (sized ~1 micron) emitted by coughing remain suspended in air, and are spread around the bus with any internal airflow. It shows that ventilation very effectively flushes the aerosols out of the space, providing confidence that ventilation can be a successful mitigation measure to help the public. The results allow quantitative analysis of concentrations of droplets, which can be used for estimates of exposure. This modelling approach enables us to assess risk reduction and mitigation strategies to lower the exposure to COVID-19 or other airborne viruses or contaminants.

Recommendations

1. **Research:** further research is needed in the UK, to determine transmission routes and realistic estimates of the infectious dose so that the contribution of airflow and ventilation can be quantified and risks of exposure can be estimated, firstly on public transport and further to this in a variety of indoor settings. Besides improving the capacity of the UK research community for emerging biological threats in the future, this approach allows a more sophisticated design of movement restrictions, based on better understanding of the risks, to help avoid a wide-spread lockdown where possible. Better understanding of the risk of transmission on public transport and in indoor public spaces, and how to reduce the risk, would allow some normal activities to resume.
2. **Informed and meaningful Guidance:** should be issued to the public how to reduce their exposure to the virus in their own homes and businesses and to raise their expectations for good ventilation and indoor AQ in the public domain. Restaurants, retail, social and leisure industries need to adapt their practices and improve ventilation so that the risk of airborne transmission is reduced. There needs to be better guidance to the public and their healthcare professionals on the risk associated with some types of activities that may not be recommended at all at some times (eg choir singing, contact sports).
3. **Practice**: Currently, indoor public spaces do not actively afford protection from infection. It is vital to lower the dose of the virus in the air, not only in hospital settings but also in other crowded public settings, such as buses, trains, stations, shopping malls, schools, and primary healthcare settings to name a few, to reduce these risks which are difficult to quantify precisely. Issuing clear guidance on the need for improving ventilation rates to a high standard is crucial, in consultation with the professional bodies and researchers. At the moment, the UK does not have guidance for IAQ on public transport. In the long term, a framework with better guidance for transport and other public places would be needed, to achieve a healthier public sphere with less risk of infection. It is also recommended that DfE AQ performance targets for schools be tightened significantly, as we have analysed those guidelines and find that many schools who still rely on natural ventilation are only required to achieve low targets for ventilation[xxiii].

   The UK has the knowledge base and the technology to achieve higher aspirations for indoor air quality and better ventilation; the existing research base, Computational modelling, large scale facilities that are being developed now such as PEARL[xxiv] and the professional institutions, can all be mobilised. If better indoor air quality targets are set and regulated in the same manner as outdoor AQ has been, we should see a substantial improvement in public health over time with positive impacts on the economy and society and better resilience to the threat of future pandemics.

Appendix – Simulations

We tested a typical scenario on a bus, including people and patterns of breathing and coughing. Figure 1 depicts such a scenario: a passenger stands just outside the cabin of a bus, the bus driver sits in their seat inside the cabin.

The simulation covers 60s of real time during which the passenger coughs 5 times (total of 15s) in the direction of the drivers cabin and then breathes normally for another 45s. The driver breathes normally over the entire period of time. The front door of the bus is open and air enters the bus at an average velocity of 0.5m/s.

Figure 2 presents isosurfaces of 0.1% of the droplet concentration (100% inside the passenger's mouth) after 60s. The droplets are well dispersed inside the driver's cabin to the left of the passenger (rear of the bus).

Figure 3 presents streamlines of the flow and contours of velocity magnitude (top) and droplet concentration (bottom) after 60s in a horizontal plane at the elevation of the passenger's head. The air enters the bus from behind the passenger and most of the air is being deflected to the right of the passenger towards the rear of the bus, however some air enters the driver's cab through gaps in the cabin's assault screen and mainly along the windshield. The passenger's previously released droplets are being transported into the cabin mainly by means of advection and the droplets are well mixed with the ambient air that was inside the driver's cabin and to the right of the passenger.

FIGURES

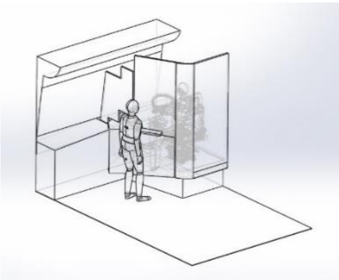

Figure 1: Computational domain and setup of the large-eddy simulation.

Figure 2: *Isosurface of 0.1% droplet concentration after 60s.* ***Left****: Oblique view from behind the passenger,* ***Right****: View from above the passenger*

Figure 3: Streamlines of the flow and contours of velocity magnitude (Left) and droplet concentration (Right) after 60s in a horizontal plane at the elevation of the passenger's head.

i https://www.gov.uk/government/publications/wuhan-novel-coronavirus-infection-prevention-and-control/transmission-characteristics-and-principles-of-infection-prevention-and-control (updated 3 May 2020, accessed 17/5/20)

ii Fineberg, H., V., et al., *Rapid Expert Consultation on the Possibility of Bioaerosol Spread of SARS-CoV-2 for the COVID-19 Pandemic (April 1, 2020)* (2020). National Academies Press. doi: 10.17226/25769.

iii van Doremalen, N. *et al.* (2020) 'Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1', *The New England journal of medicine*. NLM (Medline), pp. 1564–1567. doi: 10.1056/NEJMc2004973.

iv Hayward, A. C. *et al.* (2014) 'Comparative community burden and severity of seasonal and pandemic influenza: Results of the Flu Watch cohort study', *The Lancet Respiratory Medicine*. Lancet Publishing Group, 2(6), pp. 445–454. doi: 10.1016/S2213-2600(14)70034-7.

v Coleman, K. K. and Sigler, W. V. (2020) 'Airborne Influenza A Virus Exposure in an Elementary School', *Scientific Reports*. Nature Research, 10(1), pp. 1–7. doi: 10.1038/s41598-020-58588-1

vi Olsen, S. J. *et al.* (2003) 'Transmission of the Severe Acute Respiratory Syndrome on Aircraft', *New England Journal of Medicine*, 349(25), pp. 2416–2422. doi: 10.1056/NEJMoa031349

vii Kim, Y.I., et. Al., *Cell Host & Microbe*, ***27****(5),* p704-709, 5 2020 https://doi.org/10.1016/j.chom.2020.03.023

viii Lu, J. *et al.* (2020) 'COVID-19 Outbreak Associated with Air Conditioning in Restaurant, Guangzhou, China, 2020', *Emerging Infectious Diseases*. NLM (Medline), 26(7). doi: 10.3201/eid2607.200764.

ix Shen, Y. (2020) et al 'Airborne transmission of COVID-19: epidemiologic evidence from two outbreak investigations' (preprint. https://www.researchgate.net/publication/340418430_Airborne_transmission_of_COVID-19_epidemiologic_evidence_from_two_outbreak_investigations?channel=doi&linkId=5e87b59ba6fdcca789f10d66&showFulltext=true) (accessed 17/5/20)

x 'Choir practice turns fatal. Coronavirus is to blame.' Los Angeles Times, April 10th 2020, https://www.latimes.com/world-nation/story/2020-03-29/coronavirus-choir-outbreak (accessed 17/5/20)

xi https://www.nytimes.com/2020/03/10/nyregion/coronavirus-new-rochelle-containment-area.html (accessed 17/5/20)

xii https://www.theguardian.com/world/2020/feb/20/south-korean-city-daegu-lockdown-coronavirus-outbreak-cases-soar-at-church-cult-cluster (accessed 17/5/20)

xiii Morawska, L. *et al.* (2009) 'Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities', *Journal of Aerosol Science*. Elsevier Ltd, 40(3), pp. 256–269. doi: 10.1016/j.jaerosci.2008.11.002.

xiv Paulo, A. C. *et al.* (2010) 'Influenza Infectious Dose May Explain the High Mortality of the Second and Third Wave of 1918–1919 Influenza Pandemic', *PLoS ONE*. Edited by R. Belshaw. Public Library of Science, 5(7), p. e11655. doi: 10.1371/journal.pone.0011655.

xv Carl Heneghan, Jon Brassey, Tom Jefferson, Oxford COVID-19 Evidence Service Team, Centre for Evidence-Based Medicine https://www.cebm.net/covid-19/sars-cov-2-viral-load-and-the-severity-of-covid-19/ (accessed 17/5/20)

xvi https://www.ons.gov.uk/peoplepopulationandcommunity/healthandsocialcare/causesofdeath/bulletins/coronaviruscovid19relateddeathsbyoccupationenglandandwales/deathsregistereduptoandincluding20april2020#men-and-coronavirus-related-deaths-by-occupation (accessed 17/5/20)

xvii Qian H, Zheng X. (2018) 'Ventilation control for airborne transmission of human exhaled bio-aerosols in buildings.' *J Thorac Dis*. 2018;10(Suppl 19):S2295-S2304. doi: 10.21037/jtd.2018.01.24

xviii Hwang, S. H. *et al.* (2016) 'Relationship between culturable airborne bacteria concentrations and ventilation systems in underground subway stations in Seoul, South Korea', *Air Quality, Atmosphere and Health*. Springer Netherlands, 9(2), pp. 173–178. doi: 10.1007/s11869-015-0316-9.

xix Chen, Y. Y. *et al.* (2016) 'Indoor air quality in the metro system in north Taiwan', *International Journal of Environmental Research and Public Health*. MDPI AG, 13(12). doi: 10.3390/ijerph13121200.

xx Report of the Ministry of Environment, Republic of Korea, 2015, page 14. http://eng.me.go.kr/eng/file/readDownloadFile.do?fileId=115224&fileSeq=1&openYn=Y

xxi Guidelines for Good Indoor Air Quality in Office Premises, Institute of Environmental Epidemiology, Ministry of the Environment (1996) https://www.bca.gov.sg/greenmark/others/NEA_Office_IAQ_Guidelines.pdf, Page 44

xxii Kwon, S.-B. *et al.* (2008) 'Study on the Indoor Air Quality of Seoul Metropolitan Subway during the Rush Hour', *Indoor and Built Environment*. SAGE Publications Sage UK: London, England, 17(4), pp. 361–369. doi: 10.1177/1420326X08094683.

xxiii *BB 101: Ventilation, thermal comfort and indoor air quality 2018 - GOV.UK* (2018). (Accessed: 17 May 2020). https://www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings

xxiv https://www.ucl.ac.uk/civil-environmental-geomatic-engineering/pearl