Evidence for transmission of SARS-COV-2 on ground public transport and potential effectiveness of mitigation measures

SAGE – Environmental and Modelling Group 18052020

This paper provides the supporting scientific evidence for SAGE EMG paper Transmission of SARS-COV-2 on Public Transport (18052020). Evidence is predominately drawn from the published scientific literature together with recently published data on occupational risks. Evidence is grouped according to four questions

Evidence for close contact transmission - is there any evidence that people who do very close contact (e.g. body searches) or who do roles such as ticket checks are at a higher risk?

There is currently very little data to indicate which specific roles and activities are the highest risk for transmission for SARS-CoV-2 or other respiratory infections. While there is evidence to suggest that transport workers are at a higher risk, the specific rates among different groups of workers and the mechanisms for transmission is not clear.

Evidence for SARS-CoV-2

1. ONS data (11th May 2020) indicates that road transport drivers including male taxi and cab drivers and chauffeurs, and bus and coach drivers had significantly higher rates of death from COVID-19. This data has been adjusted for age but not for other cofounding factors such as ethnicity, comorbidities or social deprivation. Within the USA 564 TSA employees have tested positive for COVID-19, however it is not clear where exposure to the virus happens (https://www.tsa.gov/coronavirus).

2. A pre-print paper (Lan *et al.*, 2020) analysed work-related COVID-19 transmission from data in Hong Kong, Japan, Singapore, Taiwan, Thailand and Vietnam and identified 103 work-related cases. Drivers and transport workers represented 18% of cases.

3. An early case of COIVD-19 transmission was reported in Thailand. On 20 Jan 2020, a 51-year-old male taxi driver developed fever, cough and myalgia and later tested positive for SARS-CoV-2. The patient reported contact with Chinese tourist passengers in his taxi who had had frequent coughing but who wore masks. Family members who shared a house with the patient tested negative for SARS-CoV-2.

Evidence for other respiratory diseases

4. (Horna-Campos *et al.*, 2010) showed TB transmission in Lima, Peru was 2.7-4.5 times higher for transport sector workers compared to those in the total working age male and overall population of the micro-network studied. They highlight the risk for bus and microbus drivers and collectors, however do not have sufficient data to separate this out further. A previous study (Horna-campos, Bedoya and Martín, 2007) showed increase

risk of TB among the general population which was worsened with journey times greater than 1 hour.

5. Ikonen et al (2018) collected samples weekly from Helsinki-Vantaa airport in Finland. Viral nucleic acid was found in a number of areas and particularly on the buttons of payment terminals and luggage trays. Luggage trays can be handled by hundreds of people per day so it is speculated that offering hand sanitiser before and after security screening and disinfecting luggage trays more often would reduce risks.

Public transport as a transmission route - is there evidence that people have been infected on transport (for this and other diseases), is there evidence that transport moves the disease regionally?

There is a good body of evidence to associate public transport with transmission of respiratory infections from a mixture of epidemiological studies and modelling studies. While some show no association between public transport and risk, the overall weight of evidence is towards an increased risk.

Evidence for SARS-CoV-2

6. Zhao et al (2020) explored evidence for transmission of SARS-CoV-2 (Zhao *et al.*, 2020) by examining the association between load of domestic passengers from Wuhan and the number of 2019-nCoV cases confirmed in different cities. They found strong and significant association between travel by train and the number of Covid-19 cases, whereas the associations of the other two means of transportation failed to reach statistical significance (see Table below).

Transportation	Proportion*	Coeff. (per 10-fold increase)	R-squared
Train	68.72%	8.27 (0.35, 16.18), $p = 0.042$	0.26
Car	11.85%	5.7 (−6.09, 17.5), $p = 0.317$	0.07
Flight	19.42%	3.61 (−2.22, 9.44), $p = 0.206$	0.11

Note the ‘proportion’ is percentage of the transportation of interest in all transportations.

7. A pre-print paper (Qian *et al.*, 2020) analysing 318 outbreaks in China involving more than 3 people indicates that transport was the second most important category following household transmission, with 34% of the outbreaks associated with transport. It is not possible to determine from this the mode of transport or duration.

Evidence for other respiratory diseases

8. Zhen *et al.*(2020) conducted a rapid review on interventions to limit transmission of respiratory viruses on public ground transport. They identified 4 studies published since 2000, one systematic review (Browne et al 2016), one case control study (Castilla et al 2013) and two modelling studies (Furuya 2007, Zhu et al 2012). Risk is associated with seating proximity to an infected person, duration of time spent aboard and inadequate ventilation. They conclude that improved ventilation may reduce viral transmission. They advocate good public information, minimising public transport use, good environmental

control, respiratory etiquette and hand hygiene. They indicate that a risk based approach needs to guide use of non-medical masks.

9. Castilla *et al.* (2013) conducted a multi-centre case control study with 481 influenza A patients in 2009-10 in Spain. They concluded that the home environment was more important for transmission than transport. Metropolitan public transport was associated with a lower frequency of diagnosis and the use of taxis or long distance transport 7 days prior to symptoms was not significant.

10. Troko *et al.* (2011) also conducted a case-control study during the 2009 influenza season in the UK and drew very different conclusions. They found that use of bus or tram within 5 days of symptom onset was associated with a six fold increase in respiratory infection. They also indicate that regular users seem to be at lower risk than those who used public transport less frequently and suggest this may be due to better compensatory behaviours or that their frequent exposure enables them to acquire better immunity. They indicate that their findings do not support suspending mass urban transport systems during an influenza pandemic as household transmission is likely to be more significant.

11. Goscé and Johansson (2018) explore airborne transmission within the London Underground (LU) using publicly available oyster card data and PHE influenza data for London boroughs. The authors estimated passenger density and contact rates. They conclude that there is a correlation between those boroughs with higher influenza numbers and a higher number of contacts on the LU, although they note that the results do not demonstrate causation.

12. Browne et al (2016) reviewed the literature to identify the role that transport hubs for land, maritime and aviation modes play in spread of influenza and coronaviruses. It was assumed transmission was via inhalation of aerosols and/or droplets. They conclude that transport plays an important role in accelerating spread to uninfected areas, particularly air transport However, it was suggested that more work is required to evaluate the risk from land transport. They note that: “Trains have been shown to introduce influenza to new areas, but additional studies are required to quantify the level of risk.” An additional point in their discussion is the potential for contagious airport workers to infect large numbers of people with influenza.

13. Cui et al (2011) performed a contact tracing investigation on passengers of a long train journey where several people contracted flu (2009 H1N1). The results were inconclusive as to the route of infection and a number of limitations of the study were raised. They concluded that close contact and longer time on board may have contributed to the transmission. This is consistent with the review by Mohr et al (2012).

14. Nasir et al (2016) reviewed information on airborne biological disease transmission in different modes of transport. A number of factors were assessed and ranked for their likely impact on airborne infection transmission. It was suggested that proximity to source and total duration of exposure are the major factors in airborne disease transmission. Control measures were also investigated. It was stated that the literature on airborne infection transmission in various transport infrastructures is limited and mainly focused on commercial air travel.

15. Hertzberg et al (2016) examined reports of in-flight transmission of infection to assess the effectiveness of the “two row rule”. The “two row rule” is guidance from public health agencies that the primary transmission risk for respiratory infectious diseases is associated with sitting within two rows of an infectious passenger. It was found that although there is an elevated relative risk for passengers within two rows, there is still a non-negligible chance of cross infection outside the zone.

16. Hertzberg et al (2018) chronicled the behaviours and movements of individuals for single aisled aircraft over 10 transcontinental US flights. This data was used to inform a network model of contacts used to simulate transmission during flight. The model predicts that passengers in window seats will experience substantially less contacts and thus would potentially be less likely to become infected. It is speculated that passengers becoming infected while sitting far away from an infected individual happens before or after the flight.

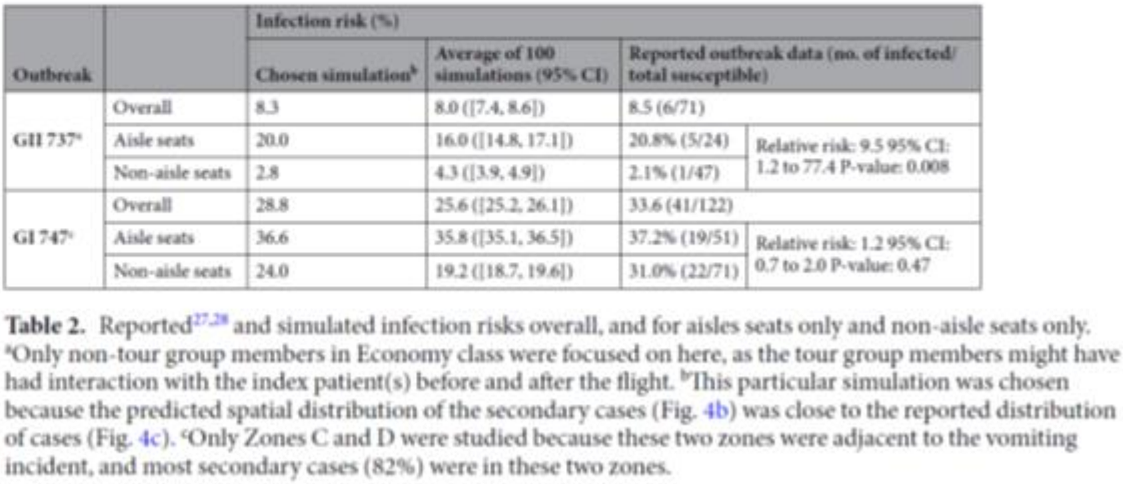
17. Yang et al. (2020) recognised the risk for transmission on long duration coach bus travel, quoting a case in China where 11 passengers were confirmed infected after sharing the “same vehicles (sic)” as the infected passenger. They identify one passenger who became infected was 4.5m away from the source and assert that this is evidence of airborne transmission. However, there is no discussion of the fomite route which may have been responsible. To explore transmission they studied droplet evaporation and transport in a bus using a CFD model under different ventilation conditions. They identified that the highest risk of transmission is to passengers close to the source and include in their recommendations that passengers sit at non-adjacent seats.

18. A study of the effect of public transport on the spread of tuberculosis in South Africa (Andrews, Morrow and Wood, 2013) using a modified Wells-Riley model for airborne disease transmission estimated the risk of tuberculosis transmission on 3 modes of public transit (minibus taxis, buses, and trains) in Cape Town, South Africa, using exhaled carbon dioxide as a natural tracer gas to evaluate air exchange. Among daily commuters, the annual risk of tuberculosis infection was projected to be 3.5%–5.0% and was highest among minibus taxi commuters.

19. A study of the transmission of 2009 H1N1 (Piso *et al.*, 2011) looked at the risk of transmission on a long bus ride. They had considered that the evidence on transmission on all public transportation systems (e.g., public trains, busses, airplanes) to be conflicted. The risk of transmission was calculated as 1.96% (95% confidence interval 0-5.76%). The study showed that very few additional passengers were infected during the trip with only one confirmed with influenza. The study concluded that the transmission rate of 2009 H1N1 Influenza was low on a long-distance bus trip.

20. In a systematic review of influenza transmission in aircraft Leitmeyer and Adloch (2016) found an overall moderate quality of evidence for transmission of influenza virus aboard an aircraft. The major limiting factor was the comparability of the studies. A majority of secondary cases was identified at a greater distance than two rows from the index case. A standardized approach for initiating, conducting, and reporting contact tracing could help to increase the evidence base for better assessing influenza transmission.

Lei et al (2017) used a novel approach to the study of surface contamination for two case studies of norovirus spread in aircraft. The approach tracked contamination on hands and surfaces and included risk of infection. The model was able to accurately simulate behaviour observed in the two case studies and may have applicability to the surface contact spread component for SARS-CoV-2. Key conclusions from the work were that flight time was important in determining the amount of spread. For example, in the table below the infection risk is considerably higher for the long haul case (GI 747). The authors note that "In less than two to three hours, most high-touch surfaces in the cabin are contaminated, and within five to six hours nearly all touchable surfaces are contaminated." For short haul flights aisle seat passengers had higher fomite exposure. This was principally because it determined the amount of use of the lavatories. Cleaning frequency was an important control. The authors recommended that chair seatbacks, particularly those on the aisle, should be included in cleaning regimes in addition to lavatories.



		Infection risk (%)			
Outbreak		**Chosen simulation**[b]	**Average of 100 simulations (95% CI)**	**Reported outbreak data (no. of infected/ total susceptible)**	
GII 737[a]	Overall	8.3	8.0 ([7.4, 8.6])	8.5 (6/71)	
	Aisle seats	20.0	16.0 ([14.8, 17.1])	20.8% (5/24)	Relative risk: 9.5 95% CI: 1.2 to 77.4 P-value: 0.008
	Non-aisle seats	2.8	4.3 ([3.9, 4.9])	2.1% (1/47)	
GI 747[c]	Overall	28.8	25.6 ([25.2, 26.1])	33.6 (41/122)	
	Aisle seats	36.6	35.8 ([35.1, 36.5])	37.2% (19/51)	Relative risk: 1.2 95% CI: 0.7 to 2.0 P-value: 0.47
	Non-aisle seats	24.0	19.2 ([18.7, 19.6])	31.0% (22/71)	

Table 2. Reported[27,28] and simulated infection risks overall, and for aisles seats only and non-aisle seats only. [a]Only non-tour group members in Economy class were focused on here, as the tour group members might have had interaction with the index patient(s) before and after the flight. [b]This particular simulation was chosen because the predicted spatial distribution of the secondary cases (Fig. 4b) was close to the reported distribution of cases (Fig. 4c). [c]Only Zones C and D were studied because these two zones were adjacent to the vomiting incident, and most secondary cases (82%) were in these two zones.

21. In a subsequent paper Lei at al (2018) examined the relative importance of airborne, close contact and fomite transmission using a modelling approach. Influenza A H1N1, SARS-CoV-1 and norovirus transmission was studies and results compared to outbreak case studies. Modelling results for the relative importance of the different routes are shown in the Table below. SARS-CoV-1 is shown to be intermediate in behaviour between influenza and norovirus with fomite transmission being most important with airborne and close contact being smaller but potentially important. SARS-CoV-1 was estimated to have a higher infection risk within 2 rows than influenza, which was also observed in the referenced outbreak cases.

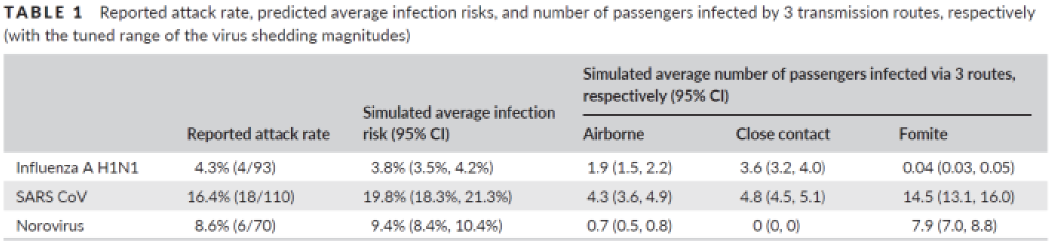


TABLE 1 Reported attack rate, predicted average infection risks, and number of passengers infected by 3 transmission routes, respectively (with the tuned range of the virus shedding magnitudes)

			Simulated average number of passengers infected via 3 routes, respectively (95% CI)		
	Reported attack rate	Simulated average infection risk (95% CI)	Airborne	Close contact	Fomite
Influenza A H1N1	4.3% (4/93)	3.8% (3.5%, 4.2%)	1.9 (1.5, 2.2)	3.6 (3.2, 4.0)	0.04 (0.03, 0.05)
SARS CoV	16.4% (18/110)	19.8% (18.3%, 21.3%)	4.3 (3.6, 4.9)	4.8 (4.5, 5.1)	14.5 (13.1, 16.0)
Norovirus	8.6% (6/70)	9.4% (8.4%, 10.4%)	0.7 (0.5, 0.8)	0 (0, 0)	7.9 (7.0, 8.8)

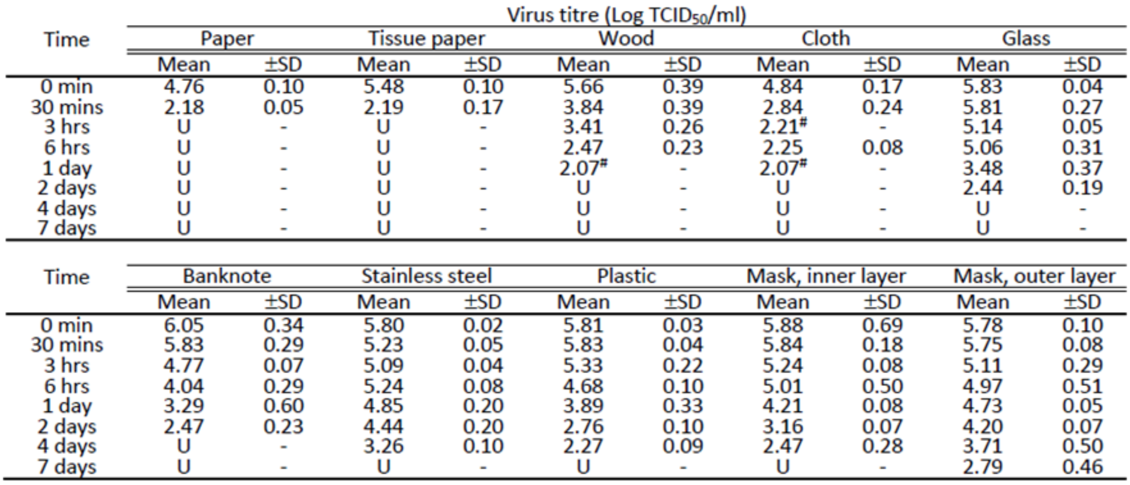
How to clean transport - evidence for survival on surfaces including fabrics as well as metal, evidence for methods and frequency of cleaning applied in a transport context. Is there potential for application of enhanced light (visible or UV) and technologies such as HPV fogging?

The evidence to date indicates that SARS-CoV-2 is likely to survive for several hours, if not days on typical surfaces within public transport. There is evidence that standard cleaning techniques will be effective and hence frequent cleaning, particularly of high touch sites is an important control. UV-C is a possible decontamination technology, but there is very little evidence for application in transport. HPV or other fumigation techniques could also be viable for terminal cleaning. Both UV-C and HPV approaches would need careful consideration of the safety aspects and extensive validation testing before they could be used. It is possible that the complexity of using such approaches outweighs the benefits compared to conventional cleaning.

Evidence of SARS-CoV-2 surface contamination

22. In a paper from the Environment and Modelling Group based on evidence from 26 April 2020, it was noted that “Recent work suggests differences in surface survival depending on the material (based on a single paper: van Doremalen et al., 2020) with SARS-CoV-2 surviving longest (up to 72 hours) on plastic and stainless steel, with a significant reduction in infectious titre over this timescale, followed by cardboard (viable up to 24 hours) and copper (viable less than 4 hours).”

23. Chin et al (2020) reported on the temperature dependence of SARS-CoV-2 survival in virus transport media. They noted that the virus is highly stable at 4°C (0.7 log-unit reduction in 14 days) but at 70°C the time for virus inactivation was only 5 min. They also examined decay on surfaces including paper, tissue paper, wood, cloth, glass, banknotes, stainless steel, mask material at 22°C and RH of approximately 65%. The results are summarised below and the authors note that no infectious virus could be detected from treated wood and cloth on day 2. The authors caution that the method used to recover virus “does not necessarily reflect the potential to pick up the virus from casual contact.”



Time	Virus titre (Log $TCID_{50}$/ml)									
	Paper		Tissue paper		Wood		Cloth		Glass	
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
0 min	4.76	0.10	5.48	0.10	5.66	0.39	4.84	0.17	5.83	0.04
30 mins	2.18	0.05	2.19	0.17	3.84	0.39	2.84	0.24	5.81	0.27
3 hrs	U	-	U	-	3.41	0.26	2.21$^{\#}$	-	5.14	0.05
6 hrs	U	-	U	-	2.47	0.23	2.25	0.08	5.06	0.31
1 day	U	-	U	-	2.07$^{\#}$	-	2.07$^{\#}$	-	3.48	0.37
2 days	U	-	U	-	U	-	U	-	2.44	0.19
4 days	U	-	U	-	U	-	U	-	U	-
7 days	U	-	U	-	U	-	U	-	U	-

Time	Banknote		Stainless steel		Plastic		Mask, inner layer		Mask, outer layer	
	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD	Mean	±SD
0 min	6.05	0.34	5.80	0.02	5.81	0.03	5.88	0.69	5.78	0.10
30 mins	5.83	0.29	5.23	0.05	5.83	0.04	5.84	0.18	5.75	0.08
3 hrs	4.77	0.07	5.09	0.04	5.33	0.22	5.24	0.08	5.11	0.29
6 hrs	4.04	0.29	5.24	0.08	4.68	0.10	5.01	0.50	4.97	0.51
1 day	3.29	0.60	4.85	0.20	3.89	0.33	4.21	0.08	4.73	0.05
2 days	2.47	0.23	4.44	0.20	2.76	0.10	3.16	0.07	4.20	0.07
4 days	U	-	3.26	0.10	2.27	0.09	2.47	0.28	3.71	0.50
7 days	U	-	U	-	U	-	U	-	2.79	0.46

* All the virus titres were titrated using Vero-E6 cells. All experimental studies were done in three independent triplicates. Detection limit of a typical $TCID_{50}$ assay is 100 $TCID_{50}$/mL, except reactions containing hand soap/chloroxylenol (detection limit: 10^3 $TCID_{50}$/mL) or reactions containing povidone-iodine/cholorhexidin/benzalkonium chloride; detection limit: 10^4 $TCID_{50}$/mL) because of their cytotoxic effects. N.D.: not done, U: undetectable.

\# Only one of the triplicate reactions was positive in the $TCID_{50}$ assay.

24. In a preliminary study, not yet peer-reviewed (Pastorino et al, 2020), SARS-CoV-2 stability was enhanced when present with bovine serum albumin, used to mimic the protein content within the body fluids of the respiratory system. Virus was still detected at the end of the 96 h experiment for the three surfaces included in the study (glass, aluminium and plastic). This may indicate that some laboratory studies underestimate surface survival.

25. The US Department of Homeland Security (DHS) (2020a) has leveraged laboratory findings to develop a predictive model and calculator to estimate the natural decay of SARS-CoV-2 under a range of temperatures (21.1°C - 35°C) and RH (20% - 60%). At present it applies to the decay of the virus in saliva on stainless steel and ABS plastic surfaces. It is anticipated that the calculator will be extended to include nitrile surfaces. At present, neither the calculator, nor supporting documentation, refer to supporting scientific papers.

26. US Department for Homeland Security (2020b) outlines preliminary results from DHS funded work at the National Biodefense Analysis and Countermeasures Center (NBACC). Key points are quoted directly below:

> “**1. Solar radiation rapidly reduces virus stability on outdoor surfaces.** Testing of virus decay in droplets of simulated saliva on a stainless steel surface was conducted at several different intensities of artificial sunlight. Sunlight intensity ranged from darkness to “full” sunlight, which is equivalent to the intensity and composition of unobstructed sunlight at noon at ground level in the MidAtlantic Region on the first day of summer. The amount of time it takes for infectious virus to be reduced by half (half-life) in a droplet of simulated saliva on stainless steel at full solar intensity was approximately 2 minutes at room temperature
>
> - Operational Relevance: This data suggests that outdoor surfaces exposed to direct sunlight are at lower risk for virus transmission.
>
> **2. Higher humidity may reduce virus survival.** When in saliva droplets, the virus is most stable at lower humidity.
>
> - Operational Relevance: This indicates that the virus is more likely to be stable and persist in areas of lower humidity. Increasing humidity levels may speed virus decay.
>
> **3. The virus dies faster at higher temperatures.** The virus is less stable in saliva droplets on surfaces than in culture media and dies faster in saliva droplets at higher temperatures.
>
> - Operational Relevance: Increased temperatures may help kill the virus and reduce transmission.
>
> **4. Bleach & Isopropyl Alcohol (IPA) are effective decontamination solutions.** Diluted bleach (1 cup in 1 gallon water) was effective in reducing virus infectivity at least >99.9% in saliva droplets

after 5 minutes on a stainless-steel surface. 70% IPA killed > 99.9% virus in a wet droplet of saliva and >98.1%virus was inactivated on stainless steel after just 30 seconds.

- Operational Relevance: Reinforces the effectiveness of these EPA recommended disinfectants for use by DHS and other entities to clean and disinfect facilities.

5. Virus stability in saliva is not dependent on droplet size. There is no statistical difference in half-life as a function of droplet size in saliva.

- Operational Relevance: Surface stability data is applicable to a broad range of droplets generated by infected individuals (e.g., talking, coughing, medical procedures)."

27. The persistence of SARS-CoV-1 has been studied more extensively. Kampf et al (2020) reviewed reported persistence on metal, wood, paper, glass, plastic and a disposable gown. Values depended on starting inoculum (viral titer) and viral strain but were typically 4-5 days. The highest value reported was 6-9 days on plastic for a higher starting inoculum.

28. Evidence from sampling on cruise liners may be relevant. Moriarty et al (2020) report that SARS-CoV-2 RNA was identified on a variety of surfaces in cabins of both symptomatic and asymptomatic infected passengers up to 17 days after cabins were vacated on the Diamond Princess but before disinfection procedures had been conducted.

29. Of 601 surfaces cruise ship surfaces sampled by Yamagashi et al 58 were positive (10%) for RNA. RNA was detected from 2/3 of case cabins but from none of the non-case cabins. Only 1 positive sample was found in a communal area. All air samples were negative. Toilet floor (39%), pillows (34%), table (24%) and chair arm (12%) were the most positive sampling sites. No viable virus was isolated. Interestingly higher percentage positive samples were found from cabins inhabited by asymptomatic cases (21%) compared to symptomatic cases (15%). Ct value found ranged from 26.2-39.0. RNA was detected up to 17 days post cabin occupation

Evidence of microbial contamination on public transport

30. Most work done of surface contamination of public transport has been looking for total bacterial counts or MRSA. Lutz et al (2014) found that 68% (27/40) of buses sampled were contaminated with S aureus, and 63% (25/40) were contaminated with MRSA. Seats and seat rails were the surfaces most frequently contaminated, followed by the back door and stanchions. Yeh et al (2011) swabbed 8 cm^2 areas on buses and found the mean bacterial colony counts were 97.1 on bus and train floors, 80.1 in cloth seats, 9.5 on handrails, 8.6 on seats and armrests at bus stops, 3.8 on the underside of seats, 2.2 on windows, and 1.8 on vinyl seats. In Bangladesh buses, Chowdury et al (2016) found grab rails were the most contaminated surface. Bacterial counts on grab rail surfaces were ranged from $(32\text{-}263)\times10^4/4cm^2$ area with a median value of almost $122\times10^4/4cm^2$. Armrests swab samples' bacterial load ranged in $(31\text{-}239)\times10^4$ whereas $(30\text{-}186)\times10^4$ were enumerated from vinyl seat samples.

31. Patel et al (2018) studied bacterial contamination within UK train stations over a year. There was a wide range in counts from individual stations. The highest median bacterial counts were 2·14 million CFU per cm^2, while the lowest were 145 CFU per cm^2. Across all stations, the median bacterial count value was 756 000 CFU per cm^2.There are multiple studies of the microbiome of subway systems. However, these are all limited to bacterial and are not quantitative, therefore they are not reviewed here.

32. Viral studies are rare. Ikonen et al sampled 1000cm^2 of areas in Helsinki airport after peak times and before cleaning. The results obtained are shown in the table below. The Ct-values of the real time PCR readouts ranged from 36.15 to 41.59 but no quantitation was attempted.

Surface	Toilets	0/42	none
Surface	Hand-carried luggage boxes at the security check area	4/8	adeno influenza A rhino human corona OC43
Surface	Armrest of a chair at the waiting area	0/6	none
Surface	Handrails of an escalator	0/10	none
Surface	Handrails of stairs	1/7	human corona OC43
Surface	Plastic toy dog in children’s playground	2/3	rhino adeno
Surface	The trolley handles for luggage	0/3	none
Surface	The buttons of an elevator	0/3	none
Surface	The touch screen on the check-in machine	0/3	none
Surface	Desk and divider glass at the passport control point	1/3	rhino
Surface	Buttons of payment terminal at the pharmacy	1/2	rhino and human corona OC43
Air	At the security check area	1/4	adeno

33. Memish et al (2013) sampled Jeddah airport for respiratory pathogens during the Hajj. Of the 58 environmental samples, 8 were positive for at least 1 pathogen. One air sample (1 of 18 samples, 5.5%) tested positive for influenza B virus. Of the 40 surface ($25cm^2$) samples, 7 (17.5%) were positive for pathogens. The viruses found were human adenovirus (3, 7.5%) and human coronavirus OC43/HKU1 (3 out of 7, 42.8%). Chair handles were the most commonly contaminated surfaces. A more recent study in hotels, malls and restaurants during the Hajj found 70/142 (49.3%) environmental samples collected were positive for at least one respiratory pathogen with 32.9% surfaces tested positive for rhinovirus and 1.4% for coronavirus. Almost 40% of door handles were found to be positive for rhinovirus.

34. A bioaerosol sampling study on Singapore's Mass Rapid Transit (MRT) network over a 12 month period collected 89 aerosol samples during peak hours. Nine (10%) tested positive for adenovirus, four (4.5%) tested positive for respiratory syncytial virus type A, and one (1%) tested positive for influenza A (Coleman *et al.*, 2018).

Evidence for cleaning related to public transport

35. (Chin *et al.*, 2020) show that common disinfectants are all effective at removing the virus, with no detectable virus after 5 min incubation. A minimum time is not given. The only exception was hand-soap solution which had a detectable level of virus at 5 min, but was undetectable by 15 min.

36. In a vehicle related disinfection study involving traditional wet surface cleaning products, Alvarez-Aldana et al, (2018) evaluated the cleaning and disinfection procedures (CDP) in six ambulances from three different locations in Pereira (Risaralda-Colombia). This study evaluated the three different cleaning products used at each site. The presence/absence of contamination was calculated from data obtained during bacterial growth assessments carried out before and after CDP. Samples were taken from three different places on the ambulances; back door, stretcher and wall next to the patient, before and after the cleaning processes. 77.8% of the samples taken were found to be positive. The most frequently isolated contaminants in the study were bacteria - Gram-positive cocci - which also remained in a greatest proportion after disinfection. The authors concluded that most of the contaminants were Staphylococcus aureus and by implementing CDP, microbiological isolates were eliminated in 33.3% overall, with the door of the ambulance area showing the greatest decrease (50.0%). It was further concluded that although a decrease in microorganisms was achieved, they were not eliminated, showing that different approaches must be considered in order to improve cleaning efficacy.

37. A supporting review from DELVE (SET-C04_02) indicates evidence from influenza that a 5 second contact can transfer 31.6% of virus to hands, although this is much lower with parainfluenza virus. There is no data yet for SARS-CoV-2. They also report data from an observational study that found face touching to be on average 23 times per hour. The DELVE paper highlights that frequent cleaning of high touch sites using common hospital level detergents is recommended; a 1:50 dilution of standard bleach is effective against coronaviruses. This review also indicates a solution with a 70% ethanol concentration is appropriate for cleaning small surfaces.

Application of UV light and fumigation technologies in transport

38. The potential application for UV and fumigation technologies for SARS-CoV-2 control in indoor environments is detailed in a companion paper (EMG - Application of UV disinfection, local air filtration and fumigation technologies to airborne microbial control - 18052020). There is good evidence that both types of technology have the potential to be effective but need to be deployed correctly. Here we include evidence for application in a transport context only.

39. There are a number of press reports that suggest UV-C decontamination devices are being used to clean buses, however there doesn't appear to be any evaluation of the efficacy of such systems in the published literature. One study assessed the use of UV-C as a terminal cleaning method in ambulances using Bacillus subtilis spores as a surrogate for pathogens. They showed that results varied significantly with surface location, with disinfection ranging from 1 to over 16 hours depending on the UV configuration within the patient compartment. They indicate that while it is a valid approach it must be validated before deployment.

40. A fumigation device generating a dry mist from 5% source hydrogen peroxide (H_2O_2) disinfectant was tested by Andersen et al, (2005) for decontamination of rooms, ambulances and different types of medical equipment. Pre-set concentrations were used via machine programming, according to the volumes of the rooms and garages. Three cycles were performed with increasing contact times using Bacillus atrophaeus spores to control the effect of decontamination. Spore strips were placed in various positions in rooms, ambulances, and inside and outside the items of medical equipment. In the ambulances, the penetration of H_2O_2 into equipment, devices, glove boxes, under mattresses, and the drivers' cabins was 100% (60/60 tests) when using three cycles, but was less effective when using one or two cycles. Decontamination was effective in 87% of 146 spore tests in closed test rooms and in 100% of 48 tests in a surgical department when using three cycles. The authors concluded that the H_2O_2 dry fumigation system, when run in three consecutive cycles, seemed to have a good sporicidal effect when used in rooms, ambulances and external and internal parts of ventilated equipment. However, it was acknowledged that further studies need to be performed concerning fumigant concentration and contact time.

41. Although not specifically focussed on vehicle decontamination, Tucker (2015) describes the application of fumigation technologies to decontaminate complex interior spaces. Undertaking work on behalf of the Lockheed Martin Corporation the assessment considered various forms of H_2O_2 product delivery, including electrostatic, ultrasonic and nebulizing spray technologies. Following test with low hazard Bacillus test spore strips the author observed up to 6.5 to 7.0 log10 reductions in spore levels in test spaces using a rotary atomizer system for delivering a fine mist from 3.5% aqueous H_2O_2. Some of the best results were achieved when a germination primary step was used to weaken spores prior to fumigation. The author concluded that the approach could potentially be used for many types of complex spaces: Aircraft, subway cars, emergency vehicles, etc.

42. Application of fumigation must consider the duration of the fumigation process (typically 30-90 minutes) together with the time and ventilation required to remove any excess fumigants. Application would need to carefully consider the amount of absorbent material present and the mechanism for aeration, as well as the location where fumigation could take place. Testing would be required to show efficacy and safety before such a system could be deployed in a transport setting.

Ventilation on transport - is there evidence to link ventilation design/use to infection risk on public transport, including aircraft.

Epidemiological evidence shows some association between poor ventilation on public transport and infection risk (here and in the sections above). There are several modelling studies that examine the mechanisms for transmission including studies that assess the role of ventilation, and preliminary calculations from CFD models show the influence of infector location and ventilation scenarios on risk to a bus driver (see Annex 1).

43. Mohr et al (2012) reviewed reported case studies of airborne infectious transmission. They discovered 14 events between 1961 and 2008. “No relevant publication was found reporting on airborne infectious disease transmission in a tram or metro/underground/subway. Of the 14 events related to airborne infectious disease transmission followed by contact tracing in ground transport, 11 events were on TB, two on meningococcal disease and one on measles. Three reported on singular exposure during single trips and 11 on events related to cumulative exposure during repeated trips.” The single trip cases reported are summarised in the table below and these have in common long exposure time. For the highest percentage of infected passengers there was no external ventilation. Where exposure time was recorded, longer exposure was related to increased proportion of infected passengers. In many of the cases reported for shorter journeys, ventilation was described as poor or used a closed system.

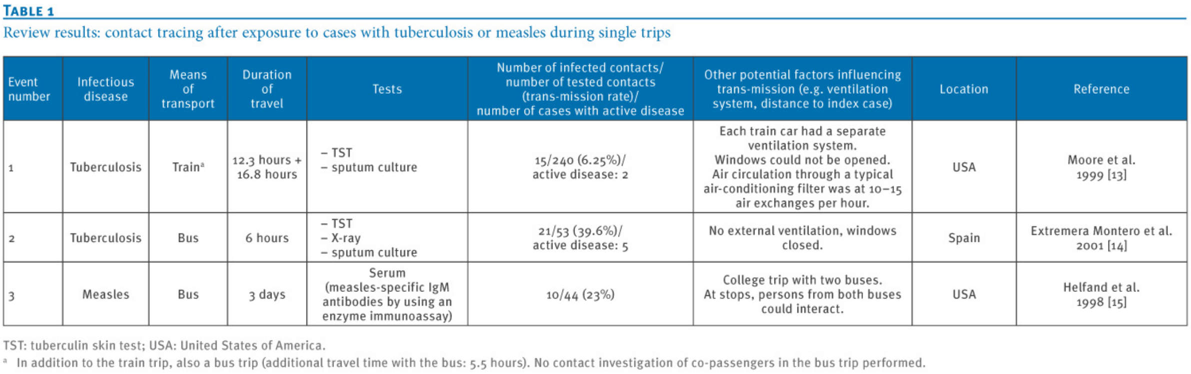


TABLE 1

Review results: contact tracing after exposure to cases with tuberculosis or measles during single trips

Event number	Infectious disease	Means of transport	Duration of travel	Tests	Number of infected contacts/ number of tested contacts (trans-mission rate)/ number of cases with active disease	Other potential factors influencing trans-mission (e.g. ventilation system, distance to index case)	Location	Reference
1	Tuberculosis	Train[a]	12.3 hours + 16.8 hours	– TST – sputum culture	15/240 (6.25%)/ active disease: 2	Each train car had a separate ventilation system. Windows could not be opened. Air circulation through a typical air-conditioning filter was at 10–15 air exchanges per hour.	USA	Moore et al. 1999 [13]
2	Tuberculosis	Bus	6 hours	– TST – X-ray – sputum culture	21/53 (39.6%)/ active disease: 5	No external ventilation, windows closed.	Spain	Extremera Montero et al. 2001 [14]
3	Measles	Bus	3 days	Serum (measles-specific IgM antibodies by using an enzyme immunoassay)	10/44 (23%)	College trip with two buses. At stops, persons from both buses could interact.	USA	Helfand et al. 1998 [15]

TST: tuberculin skin test; USA: United States of America.

[a] In addition to the train trip, also a bus trip (additional travel time with the bus: 5.5 hours). No contact investigation of co-passengers in the bus trip performed.

44. Askar et al (2012) reviewed the importance of ground transport compared to air travel, noting that ground transport accounted for 16.8% of passenger volume compared to 0.2% for air transport for Germany in 2007. They note that HEPA filtration is commonly used in airplanes but not in ground transport vehicles. They reviewed a small number of modelling studies on airborne infection risk. One of these studies Furuya (2007) looked at airborne transmission of influenza within a train carriage using a model based on the Wells-Riley equation and a probability of infection model. They calculate the reproduction number for the environment. They also looked at using masks – surgical and HEPA with penetration fractions of 0.6 and 0.03 respectively (based on Noakes *et al* (2006)). It

concluded that the HEPA masks were effective at reducing R, surgical masks somewhat effective and doubling the ventilation rate had a considerable effect. The authors also found that risk increased linearly with exposure time, and the number of passengers also increased the risk. However, Askar et al (2012) note that even though simulation models demonstrate the potential influence of different environmental conditions on the risk of airborne disease transmission, evidence from experimental and microbial investigations in real events is still insufficient.

45. Leder and Newman (2005) reviewed respiratory infections during air travel, considering influenza, tuberculosis, measles and SARS-CoV-1. They noted that most aircraft operate with 50% recirculated air with HEPA filtration that remove 99.9% of bacteria and viruses. They report on one study (Zitter et al, 2002) that examined the role of air recirculation as a predictor of postflight upper respiratory infection. Reported results were similar, suggesting that aircraft cabin air recirculation does not increase the risk for upper respiratory symptoms. Leder and Newman (2005) also note that “The SARS virus is spread predominantly by contact with respiratory droplets from an index case or by direct contact with contaminated hands or objects, although airborne transmission also occurs.” They discuss the case study of a doctor who had contact with a SARS-CoV-1 patient flew from New York to Germany. He was isolated at the back of the plane with his family (who included individuals also incubating SARS-CoV-1). A flight attendant who had brief contact with them while serving and picking up their food trays developed probable SARS four days later. No other crew members or unrelated passengers contracted SARS. Passenger to passenger transmission of SARS has also been reported. In the most serious case one symptomatic individual was associated with potential transmission to 22 people, including 8 out of 23 people seated in three rows in front of the index case and 10 out of 88 people seated elsewhere. The authors also note that: “The greater concentration of illness in people sitting in front of the index case than behind suggests a role of coughing in transmission, possibly with a combination of airborne and droplet spread.”

46. An outbreak of influenza on an aircraft that was grounded for over 3 hours and resulted in 72% of the 54 passengers becoming infected demonstrates the risk of transmission under very poorly ventilated conditions (Moser *et al.*, 1979). The aircraft had no ventilation system switched on so relied on infiltration via the open door.

47. An experimental study of natural ventilation for tuberculosis control in minibus taxis in South Africa showed that configurations with two open windows could achieve ventilation rates close to or exceeding WHO requirements for high risk clinical areas (Matose et al 2019). Using exhaled CO2 as a marker, they showed that with windows closed the CO2 concentration on a fully occupied bus (16 people) could rise to above 3500ppm, while opening 2 or more windows quickly reduced the concentration to 500-1000ppm.

48. Although not public transport, an experimental study with a cough simulator in an ambulance showed that the ventilation rate had a significant influence of exposure to airborne particles (Lindsley *et al.*, 2019). Increasing the air change rate from 0 to 5 ACH reduced the mean concentration by 34%, while increasing to 12 ACH reduced the concentration by 68%. Exposures were not significantly different at different locations within the compartment.

49. Zhu et al (2012) used CFD combined with the Wells-Riley equation to assess the risk of influenza transmission on a bus. Multiple ventilation modes were evaluated. Previous experimental work was used to support some of the assumptions. Different ventilation configurations were tested. It was concluded that displacement ventilation minimises the air mixing and hence the risk of infection spread between passengers compared to typical ventilation configurations where dirty air is drawn to a single extract point.

50. There are several studies that model ventilation flows in aircraft cabins including (Wan *et al.*, 2009; Gupta, Lin and Chen, 2011; You *et al.*, 2019). These all show the importance of the cabin airflow pattern in dispersing airborne droplets and provide a useful resource for understanding ventilation system design. Extending the focus to other environments, Noakes (2009) provides a review of different models for transmission within a hospital ward. One conclusion states that high fidelity analysis like CFD is essential to show how the location of ventilation supply and extract vents influence the risk of cross-infection between patients.

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Annex 1: Computational modelling paper from UCL group

UCL DEPARTMENT OF CIVIL, ENVIRONMENTAL
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UCL

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*"[1], 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"[2]. 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[3]. 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[4].
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[5]. 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[6].
4. A recent study found SARS-CoV-2 to be viable in suspended aerosols for at least 3 hours[3]and concluded that aerosol transmission is plausible. A report released last week[7], 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[8], 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[9]. 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[10]; the first large cluster identified in the US, which centred around over 100 infections at a synagogue in New York state[11]; 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[12]. 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[13].
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[14] and might also worsen the severity of COVID-19 disease[15], 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[16].

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[17]. 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[18]. In Taiwan's Taipei Metro system, bacterial concentrations were also found to be higher than their regulations allow for[19].
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[20]. 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[21]. 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[22].

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[23].

   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[24] 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

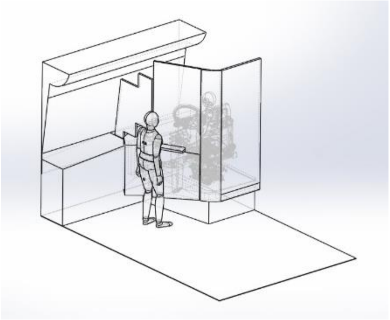

Figure 1: Computational domain and setup of the large-eddy simulation.

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

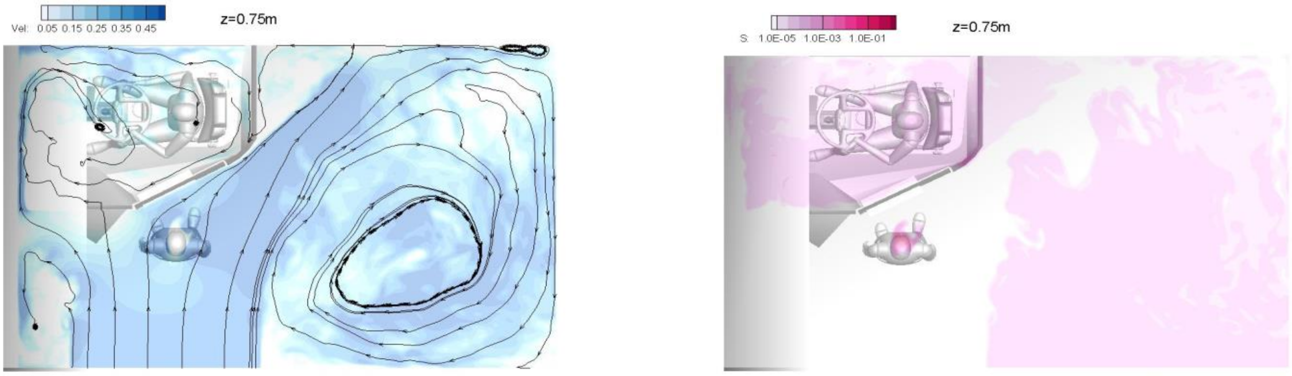

Figure 3: Streamlines of the flow and contours of velocity magnitude (Left) and droplet concentration (Right) after 60s in a horizontal plane at the elevation of the passenger's head.

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