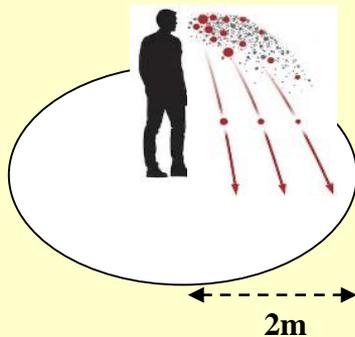


FSEG COVID-19 Mitigation Analysis Using CFD and Agent Based Models

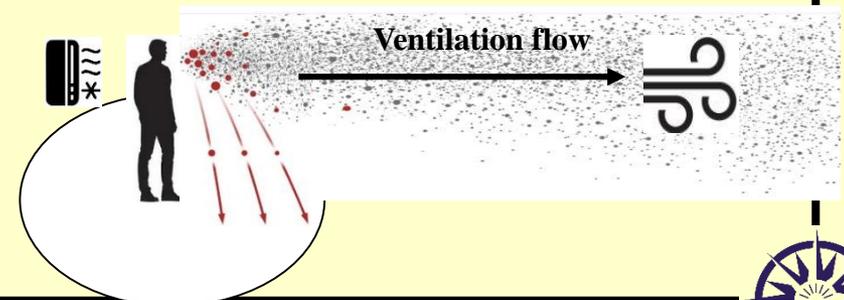
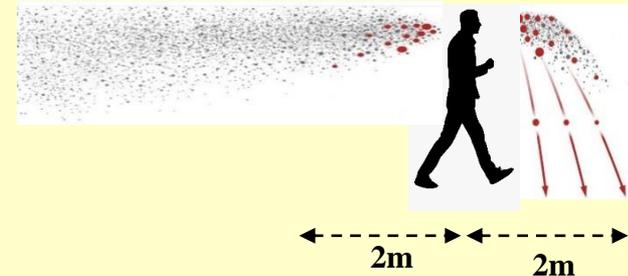
Prof Ed Galea
and

Dr John Ewer, Mr Lazaros Filippidis, Mr Ian Frost, Dr Angus Grandison,
Dr Fuchen Jia, Dr Peter Lawrence, Prof Mayur Patel, Dr Zhaozhi Wang

Fire Safety Engineering Group
University of Greenwich
UK



OR

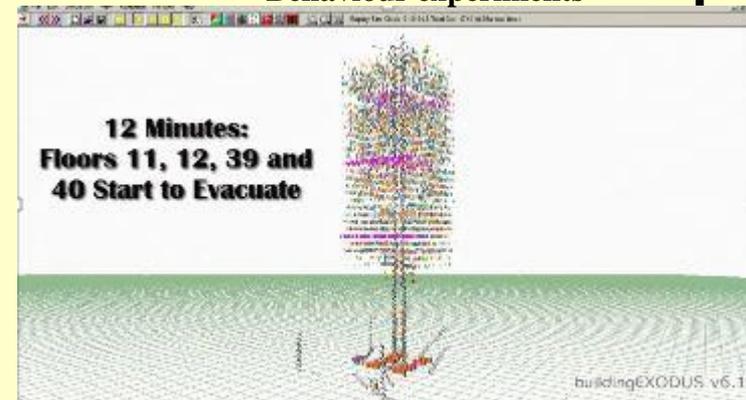


FSEG: Modelling safety and security

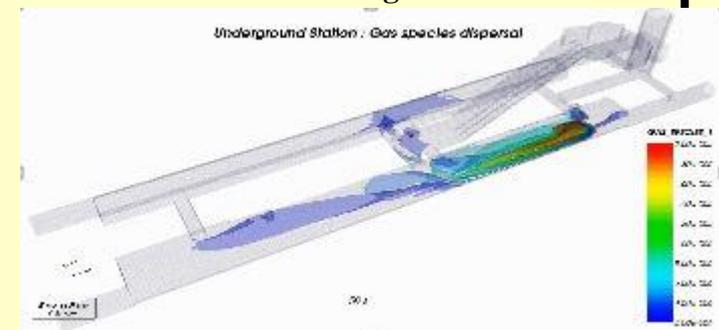
- FSEG was Founded in 1986 by Prof Galea in response to the Manchester Airport B737 fire.
- Today it consists of 20 researchers including:
 - fire engineers, CFD specialists, psychologists, mathematicians and software engineers.
- Research interests include the **mathematical modelling** and **experimental analysis** of:
 - evacuation dynamics in complex spaces,
 - urban-scale evacuation,
 - pedestrian dynamics in complex spaces,
 - combustion and fire/smoke spread,
 - fire suppression,
 - security
- Application areas include:
 - aviation, buildings, maritime and rail.
- Developed EXODUS and SMARTFIRE tools
 - Both under continual development since 90s
 - Extensive validation history
 - Users in over 35 countries



Behaviour experiments



EXODUS agent model

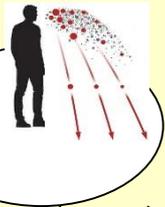


SMARTFIRE CFD fire model

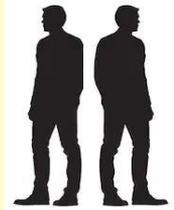


THREE ROUTES TO SARS-CoV-2 INFECTION

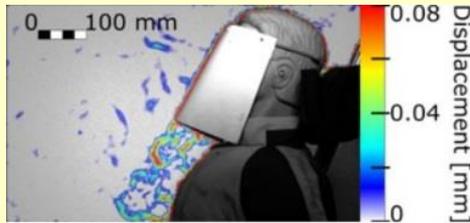
- **(1) Large Droplets:** large respiratory droplets ($> 100 \mu\text{m}$) follow ‘cannon ball’ projectile trajectories and fall to the ground within $\sim 2\text{m}$ in a few seconds – susceptibles within $\sim 2\text{m}$ can inhale large falling droplets or they can impact eyes.
 - Hence recommended: 2m physical distance, avoid directly facing someone in queues or seating in offices, face shields, partial screens and one way flows.



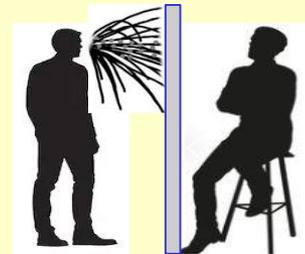
2m



< 2m



< 2m



2m



- **(2) Fomit infection:** Associated with large droplets that fall onto surfaces contaminating them. Touching the surface and then your face, mouth or eyes causes infection.

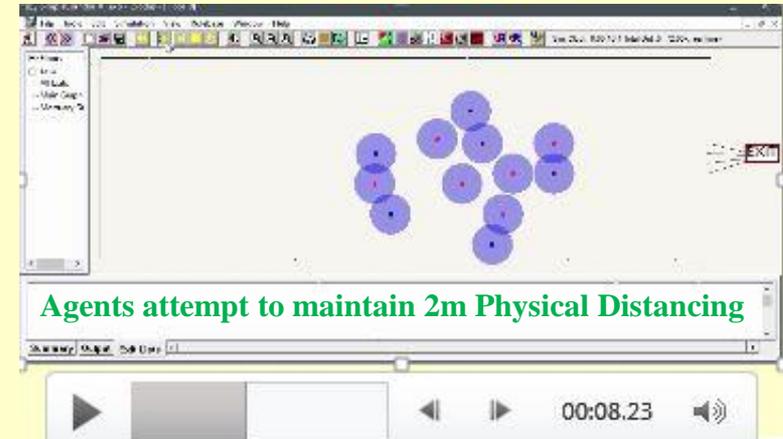
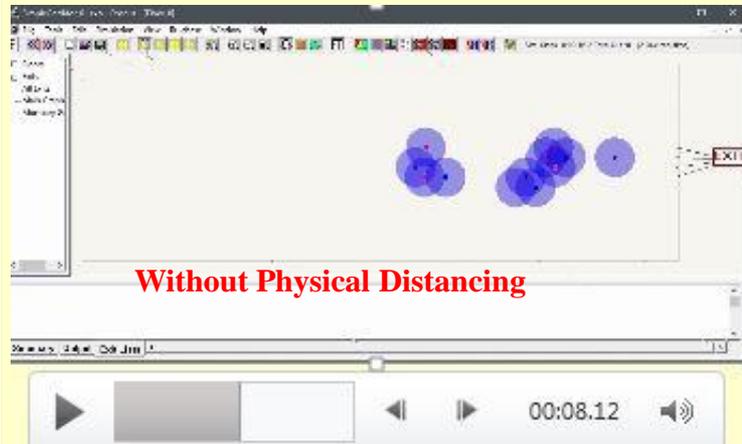
- Hence recommended: hand hygiene.

- However, CDC now claim only 0.001% IP



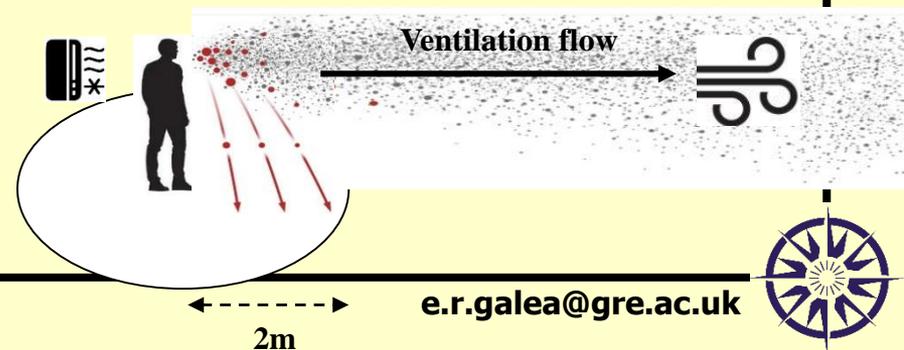
Simulating imposed physical distancing within EXODUS (ABM)

- EXODUS ABM has been modified to take into consideration agents efforts to maintain physical distancing, which is not always successful - circle radius = 1m.
- Results in less crowding at exit point, time to empty space increased by 19%.
- **Can be used to assess impact on capacity, flow and level of service.**



- **(3) Airborne infection:** small respiratory droplets ($< 100 \mu\text{m}$). These aerosols can be dispersed throughout the space, carried by thermal currents, ventilation AND wake flows. Aerosols can remain suspended in the air for hours even after source has left.
 - Hence recommended: face coverings and high ACH.

• ABMs, on a building scale, ignore aerosol dispersion, the impact of air-conditioning systems and the impact of agent generated wake flows – questionable value for assessing IP and mitigation strategies.



Aerosol dispersion using CFD - SMARTFIRE

- **Rapid prototype development of new modelling capabilities for aerosol dispersal based on core SMARTFIRE CFD fire simulation software;**
 - RANS, with k-eps turbulence model, with Lagrange water mist model including particle/air momentum coupling, particle drag and evaporation.
- **Enhancements include capability to:**
 - **Represent aerosol dispersion as evaporating particles or passive scalar.**
 - **Simulate recirculating HVAC with filtration and wake flows due to dynamic movement, through RNG K-eps and Immersed Boundary Method.**
 - **Couple CFD with Wells-Riley equation to determine infection probability (IP) based on CFD predicted aerosol dispersion, $p = 1 - e^{-Iqvt/Q}$**

Model Verification and Current Applications:

- **Attempt to verify model using analysis of critical indoor infection risk scenarios/events.**
- **Explore diverse indoor environments to evaluate IP and investigate mitigation strategies.**

Publications:

- **'Inflight Transmission of COVID-19 Based on Experimental Aerosol Dispersion Data', Z Wang, E R Galea, A Grandison, J Ewer, F Jia, Journal of Travel Medicine, 2021; <https://doi.org/10.1093/jtm/taab023>**
- **'CFD Based Analysis of COVID-19 Infection Risk on Chinese G-Trains'. In preparation.**
- **'Source Terms for Benchmarking Models of Aerosol and Droplet Disease Transmission', M. Stettler et al., in review. Journal of the Royal Society Interface, 2021. (RAMP Task 7)**

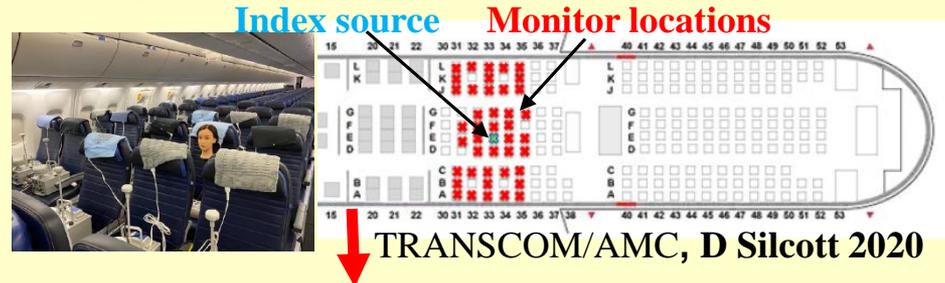


Inflight Transmission of COVID 19

Inflight transmission of COVID-19 based on experimental aerosol dispersion data 

Zhaozhi Wang, PhD, Edwin R Galea, PhD , Angus Grandison, PhD, John Ewer, PhD, Fuchen Jia, PhD

Journal of Travel Medicine, taab023, <https://doi.org/10.1093/jtm/taab023>



Non-uniform measured **Breathing Zone Penetration (BZP)**

Modified Wells-Riley Model

$$p = 1 - e^{-qrt_1 - q((1-a)(1-b)r)t_2}$$

r: measured individual **BZP (inhaled/released)**, **q**: quanta source

- Max individual IP (without masks) for 2-hr flight, varies from **4.5%** for 'Mild Scenario' to **60.2%** for 'Severe Scenario', with average IP from **0.1%** to **2.5%**;
- **C/W statistical study based on data from 291 flights (M. Hu, 2020)**: max individual IP **10.1%** and average IP **0.7%**;
- For 12-hr flight, max IP varies from **24.1%** to **99.6%** with average IP from **0.8%** to **10.8%**.
- Face mask can reduce average IP by **73%**, but removing for 1 hr meal service increases IP by **59%**.

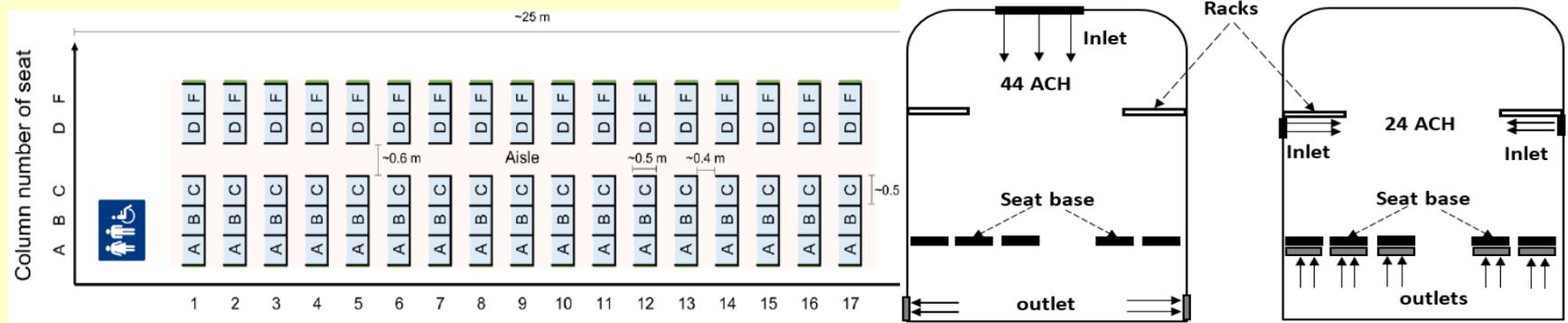
Experimental Observation:

Aerosol rapidly diluted, min reduction, **99.7%** (pax near source); and average reduction of **99.99%** for the 40+ monitored points in each cabin section

Concluded: Aerosol exposure risk is **minimal** even during long duration flights, but typically highest in index patient row



Verification Case: Actual COVID 19 Transmissions on G - Train



Floor configuration of typical G-train carriage

Two typical ventilation configuration

Statistical Analysis by M Hu et al., 2020

- **G-train**—high speed trains in China; typical carriage: 17 rows with 5 seats abreast ;
- Two typical ventilation configurations: Inlet: ceiling, Outlet: floor-level side-walls (**44 ACH**) and Inlet: side-walls under racks, Outlet: seat bottoms (**24 ACH**);
 - **Note: ventilation rates for UK trains are much lower, 8-10 ACH.**
- Involving **2,334 index patients** and **72,093 close contacts** (seated within three rows of index) with co-travel times of **0–8 hours** from **19 Dec 2019 to 6 Mar 2020**;
- The attack rate for paxs seated within 3 rows and 5 columns of an index patient varied from **0 to 10.3%**;
 - Maogui Hu, et al, "The risk of COVID-19 transmission in train passengers: an epidemiological and modelling study," *Clinical Infectious Diseases*, no. <https://doi.org/10.1093/cid/ciaa1057>, 2020.



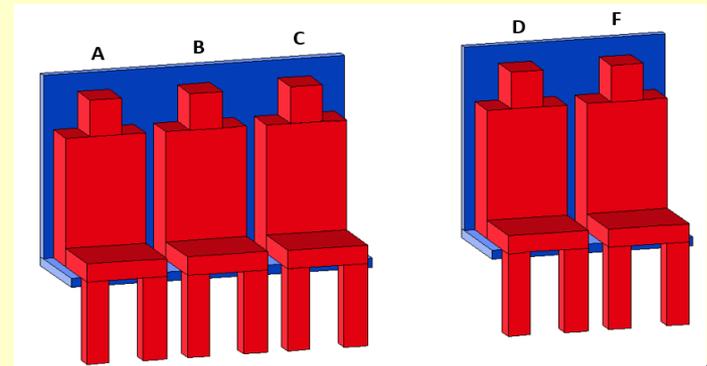
G-train CFD Aerosol Dispersion Model

Investigation Methodology: Coupled CFD + Wells-Riley Model

- Respired aerosol droplets modelled using a *scalar gas release*;
- Predicted CFD scalar concentrations are first converted to quanta concentrations;
- Individual IP are derived using modified WR model and simulated local quanta concentrations;

CFD Simulations

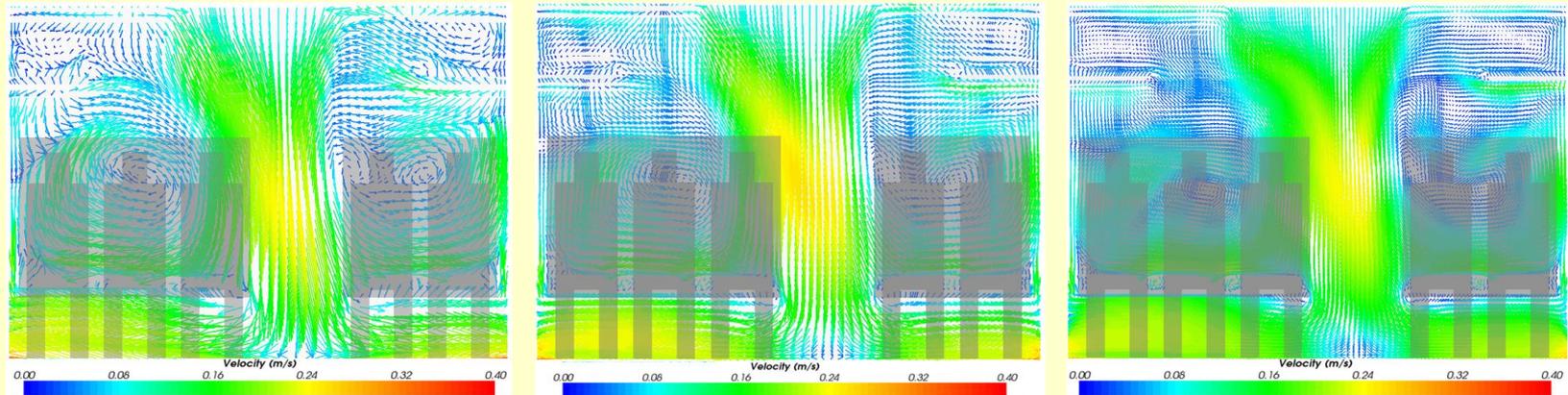
- **Seats/Paxs:** represented as obstacles, paxs have 50 W/m² surface heat release rate;
- **Two saloon ventilation scenarios considered:**
 - Scenario 1: Top inlet with a ventilation rate of 5500 m³/h (44 ACH);
 - Scenario 2: Side wall inlets with a ventilation rate of 4000 m³/h (24 ACH).
- **Ventilation System:** mass ratio of **recirculated** to dumped air in Scenario 1 / 2 is 0.66 / 0.59
- **Ventilation filtration efficiency:** 20%;
- **One index patient** per simulation per scenario.
 - Five different seating locations per scenario, Seat 6A, 6B, 6C, 6D and 6F;
 - Five simulations per scenario.
- **Quanta generation rate:** 14 quanta/h is assumed.
Representative of resting infectious individuals
(Wang et al 2021)



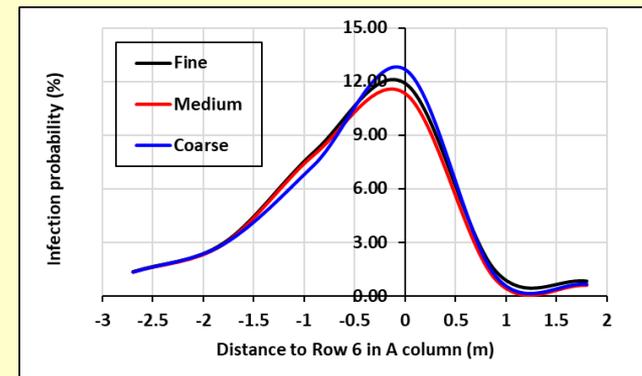
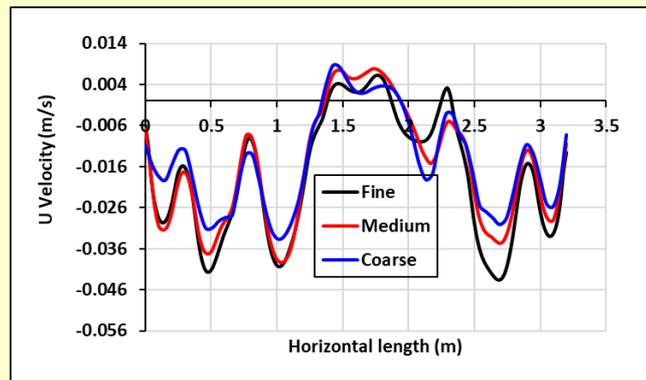
G-train CFD Aerosol Dispersion Model

CFD Simulations

- **Mesh sensitivity** analysis: coarse, medium and fine cases, with computational cells of 1,095,444 (378×46×63), 2,245,320 (378×60×99) and 5,091,240 (399×88×145) respectively.
- The **medium mesh** is applied in all CFD simulations; a quasi-steady-state reached within 990s, requiring **60 hours of computation** per simulation.



Velocity distribution in the cross plane for the Coarse, Medium and Fine mesh



Simulated velocity and infection probability along lines for the Coarse, Medium and Fine mesh cases



G-train – Estimation of COVID 19 Infection Risk

Modified Wells-Riley Model

$$p = 1 - (1 - x)^2 e^{-cvt} - x(1 - x) \left(e^{-(1-a)cvt} + e^{-c(1-b)vt} \right) - x^2 e^{-(1-a)c(1-b)vt}$$

Where:

- p is infection probability; x is probability of a passenger (or proportion of population) wearing a face mask; c is **quanta concentration in the target volume derived from a CFD simulation**; a is mask efficiency for index, b is mask efficiency for susceptible; t is exposure time;
- q : 14 quanta/h; x : 40%; a : 50% and b : 30% respectively; $t = 1, 2, \dots, 8$ h
- **Quanta concentration distribution rapidly reaches a quasi-steady-state after about 900 s.**
- **Apart from end effects, seating row number has little impact on distribution.**
 - **Seat row location for study based on seat row 6.**
- **For verification study, results for each scenario are based on a weighted average of index patient located in seats 6A, 6B, 6C, 6D, 6F where weighting derived from provided data.**
 - **Model predictions involve a simple average of results from Scenario 1 and 2.**
- **For the general study, simple average of the 5 seat locations across both scenarios is presented unless otherwise stated.**



G-train verification study, estimation of COVID19 IP

Maximum infection probability

- **10.3%** at seat locations adjacent to index patient as reported by M Hu, 2020;
- **14.7%** predicted by simulations (average for 10 index cases in the two ventilation scenarios)

Highest/lowest infection probability (average travel time 2.1 hours)

Reported infection probability:

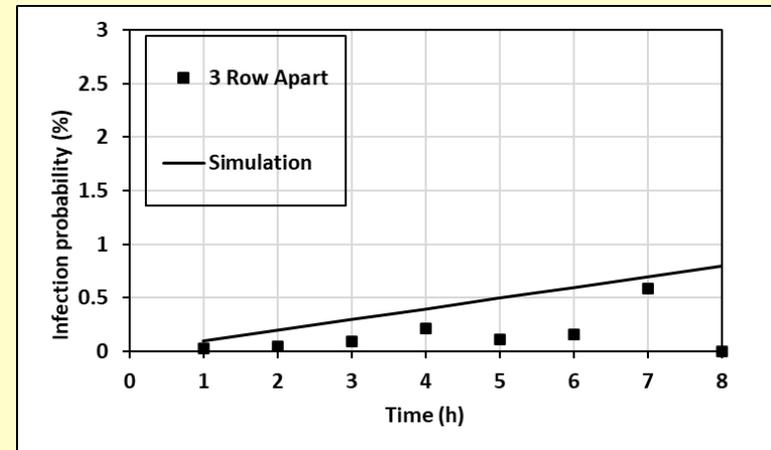
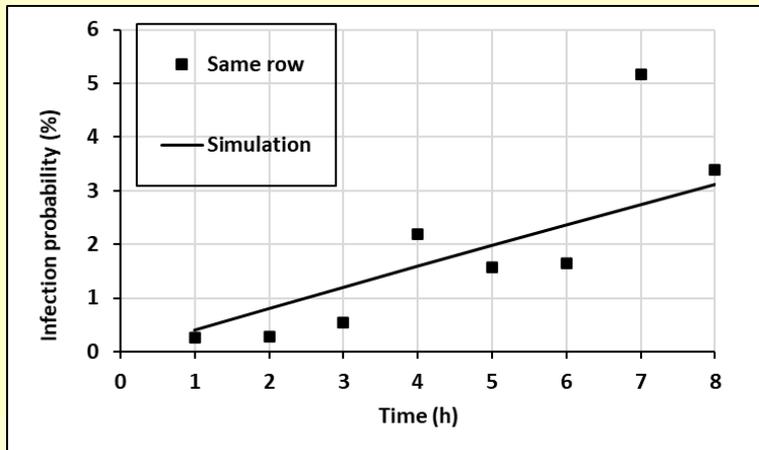
0.28% 0.41% 0.34% 0.34% 0.27%



Estimated infection probability:

0.56% 0.70% 0.55% 0.63% 0.53%

- **Infection probability as function of distance to index patient and exposure time.**



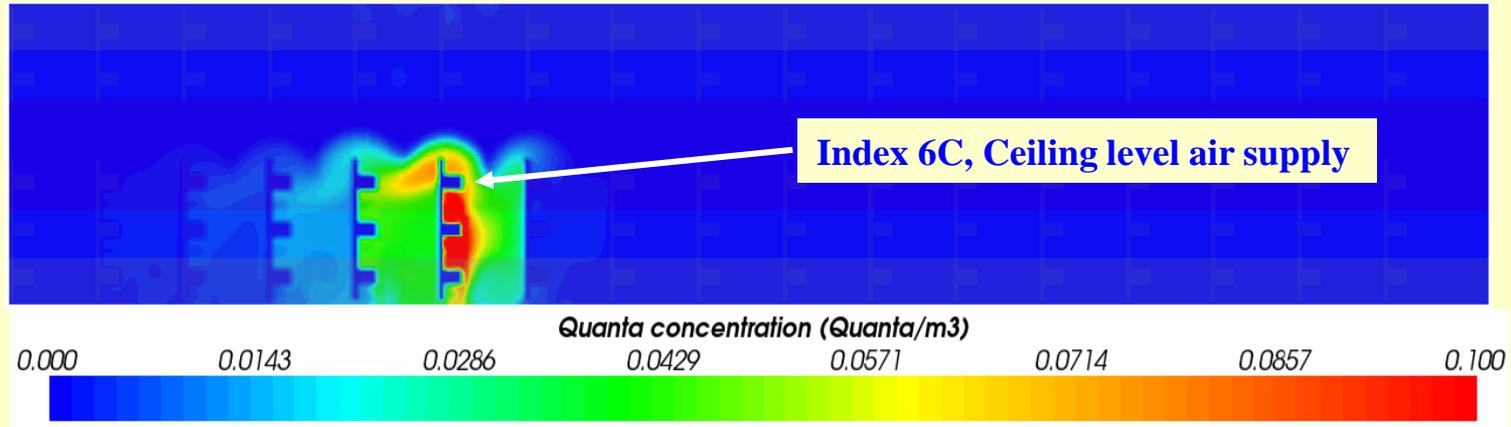
Same seat row as the index patient (symbol: reported data) Three seat row away from the index patient



G-train – Estimation of COVID 19 Infection Risk

Asymmetry in quanta distribution and IP in Scenario 1 with index patient in 6C

- Very high quanta conc up to 2 seat rows behind index patient;
- Lower quanta conc in seat row ahead of index patient;
- Seat block with index patient has significantly higher quanta conc than seat block opposite;
- Asymmetry of quanta distribution results in asymmetry in IP.
- IP of 0.5% at locations far from the index patient is due to recycled quanta.
- Conventional WR model with well mixed assumption CANNOT reproduce these observations.
- Questionable validity of rigid 2m separation and concept employed by agent-based models.



Quanta concentration distribution excluding recycled background distribution

F	0.5	0.5	0.5	0.6	0.7	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
D	0.5	0.5	0.6	0.7	0.7	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
C	0.7	0.8	1.6	3	10.4	1.1	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
B	0.6	0.9	1.5	3.1	8.7	25.3	1	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
A	0.6	0.8	1.3	2.8	7.6	12.1	0.9	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

IP (%) distribution for 8-hour G-train travel Scenario 1 (recycled quanta contributes 0.5%)

Exploring various non-pharmaceutical mitigations

- **Model used to explore a range of mitigation strategies and impact of ventilation conditions.**
 - Unless stated otherwise, results are for average of Scenario 1 and 2 with 20% FE, 8 hr exposure, 63% recycled air and averaged over the 5 index seating locations
- **Ventilation filtration efficiency (FE):**
 - Increasing FE to 100% results in negligible decrease in max IP, **15.8%** compared with **16.1%** for the 20% FE case, however,
 - Average IP reduces from **1.21%** to **0.69%** i.e. **1.02** secondary infections to **0.58**.
- **Ventilation rate (VR): (based on Scenario 1 and Index in 6C only)**
 - Reducing VR from 44 ACH to 14 ACH reduces the max IP from **25%** to **11%**.
 - However, average IP increases from **1.4%** to **2.6%** i.e. **1.1** secondary infections to **2.2**.
- **Impact of Mask Wearing (MW):**
 - With 40% paxs wearing surgical masks, average IP **1.21%**, **1.02** secondary infections
 - Increasing MW to 90%, average IP and secondary infections reduce to **0.7%** and **0.6**.
 - With 90% MW and high efficiency masks (90%), average IP and secondary infections **drop significantly** to **0.06%** and **0.05**.
- **Seat Blocking Strategies: (assuming 1 Index per 85 paxs)**
 - 3 seat blocking strategies explored, reducing paxs from 85 to 51, 45 and 27.
 - Note: IP dependent on location of index patient.
 - Most effective involves occupying A, C and F seats in odd rows
 - Reduces number of paxs per saloon from 85 to 27
 - Reduces average IP from **1.21%** to **0.63%** i.e. **1.02** secondary infection to **0.16**.
 - However, must run 3.15x as many saloons.
- **MOST EFFECTIVE STRATEGY IS TO ENSURE 90% OF PAXS WEAR HIGH EFFICIENCY MASKS (CORRECTLY).**



Exploring the impact of vaccinations

- Consider G Train (average of Scenario 1 and 2), 40% pax wear face masks; assuming:
 - Index patient is not vaccinated,
 - For the **B.1.617.2 variant**, recent (22 May 2021) PHE data suggests for **any** vaccine
 - 51% of the pop have received 1 vaccination dose (effectiveness of 33.5%)
 - 30% of pop have received 2 vaccination doses (effectiveness of 80.9%);
- The average infection probability for the partially vaccinated population (p_v) is related to the previously calculated infection probability of the non-vaccinated probability (p_{nv}) by:

1 dose *2 doses* *0 dose*

$$p_v = p_{nv} \times (0.51 \times (1 - 0.335) + 0.3 \times (1 - 0.809) + 0.19 \times 1) = 0.586p_{nv}$$

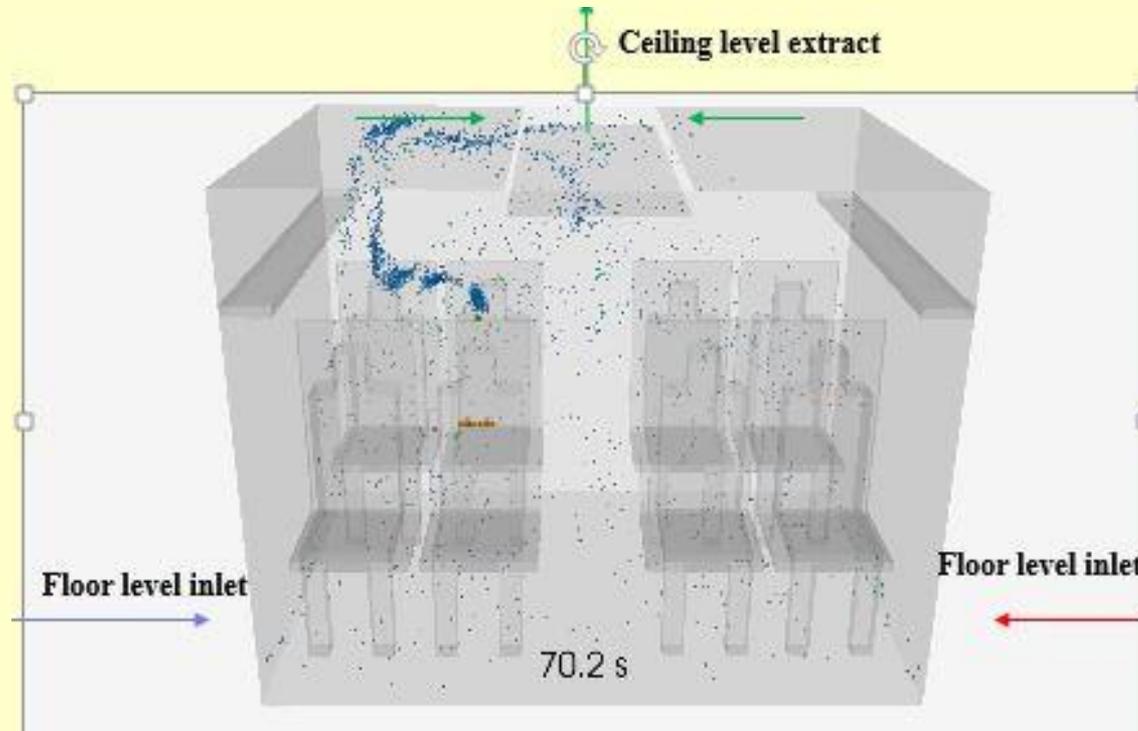
- Average Max IP (irrespective of location) is reduced from **16.0%** to **9.4%**;
 - Maximum average IP is reduced from **8.9%** to **5.2%** ;
 - Average IP and secondary infections reduced from **1.21%** to **0.71%** and **1.02** to **0.60**;
- Furthermore, in addition to reducing the IP, the risk of likely hospitalisation after vaccination is reduced by ~90%. (PHE)

	F	0.6	0.7	1	1.9	4.4	4.1	0.9	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	D	0.6	0.7	1.1	2	4.8	5.4	0.9	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Average		Without vaccination																
	C	0.6	0.7	1.1	1.8	4.6	7	0.9	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	B	0.6	0.7	1.2	2.2	5.2	8.9	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	A	0.6	0.7	1.1	2.1	5.1	6.5	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	F	0.3	0.4	0.6	1.1	2.6	2.4	0.6	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	D	0.3	0.4	0.6	1.2	2.8	3.2	0.5	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Average		With vaccination																
	C	0.3	0.4	0.6	1	2.7	4.1	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	B	0.3	0.4	0.7	1.3	3.1	5.2	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	A	0.3	0.4	0.6	1.2	3	3.8	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Infection probability (%) distribution for 8-hour G-train travel with/without vaccination



Demonstration of SMARTFIRE Particle Model for Respiratory Particles



- 10 ACH, approximately 67% of air-conditioned air is recycled
- Train filtration system generally low quality i.e. not HEPA filters – 20% filtration efficiency
- Return air contains respiratory aerosols uniformly seeding the environment.
- The droplet/aerosol source is represented by a sinusoidal breathing model (Gupta et al, 2010)
- The respiratory droplets/aerosols follow the “BLO” size distribution of Johnson et al. (2011)



Immersed moving boundary condition with droplet dispersal

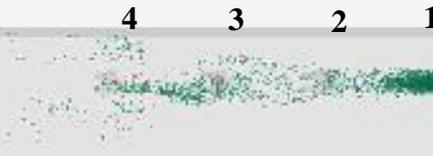
- Is 2m spacing adequate in corridors? ABM implicitly assume this is acceptable.
- Each figure is separated by 2m, height and walking speeds are identical.
- Lead figure is the Index Patient, 3 following figures are constantly bathed in aerosols.
- Staggered walking configuration significantly reduces exposure to respired aerosols
- Note the persistence of the aerosol cloud.

Single file with 2m separation
Side view



Single file with 2m separation
Plan view

4 3 2 1



Diagonal formation with 2m separation
Plan view

20.8 s

2 1

4 3

20.8 s

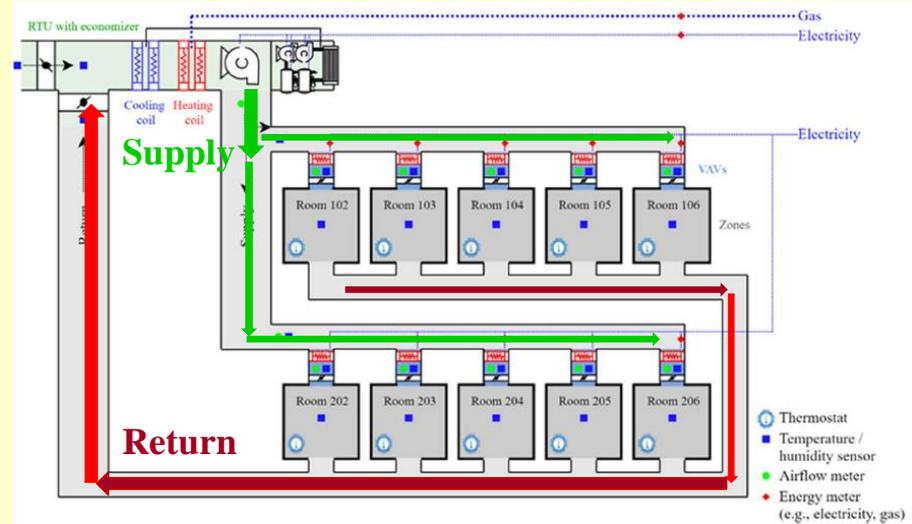


Potential Infection Risk Via Air Conditioning System

Aerosol Experiment (Chien et al 2021)

medRxiv preprint doi: <https://doi.org/10.1101/2021.02.25.21252239>

- The facility is a typical two-floor (10 rooms) **office building**;
- A central HVAC system provides variable air volume with ventilation rates between 5.4 ACH and 9.3 ACH for rooms;
- There is a exhaust fan in the core room;
- The supplied air includes **90% recycled air** from the 10 rooms as seen in the figure below;
- The flow rate is 11 L/min from the aerosol generator but the particle generation rate was not measured; (most particles are less than $0.5 \mu\text{m}$);
- Two experiments undertaken involving all room doors open or closed;
- Heaters are set to emulate human occupancy but the locations and heat release rates are not reported;
- Particle mass concentrations measured at various locations;
- In the experiment with closed doors, the particles mass concentrations under the diffuser of the HAVAC suppliers are $17 \mu\text{g}/\text{m}^3$ in the source room and $2.5 \mu\text{g}/\text{m}^3$ in non-source room, with a **ratio of 6.8**



Centralised HVAC system to supply and return air



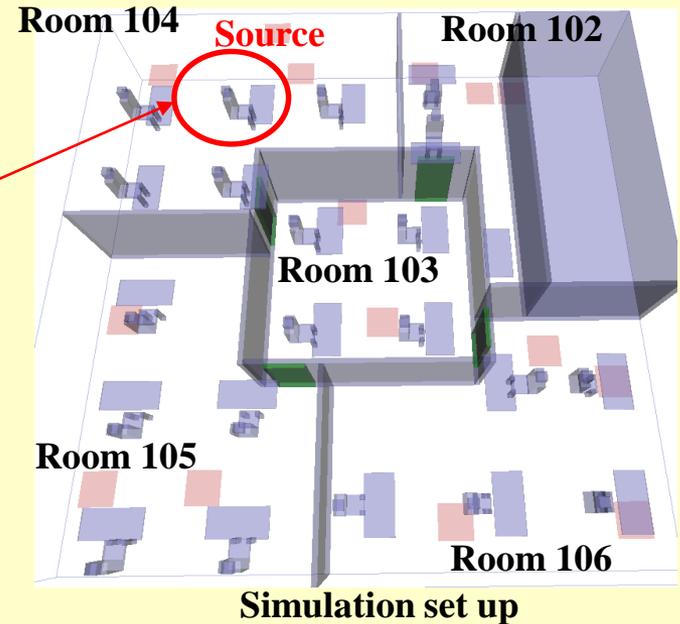
IP Within Air Conditioned Buildings

Coupled CFD+Wells-Riley

Aerosol Experiment (Chien et al 2021)

medRxiv: <https://doi.org/10.1101/2021.02.25.21252239>

- Preliminary CFD analysis, note there are many uncertainties in the experimental setup.
- Particle source (<0.5 μm) simulated as gas scalar;
- Air filtration efficiency is reported low; assumed 10%;
- All internal doors are closed but rooms connected via HVAC with 90% of air recycled;
- Source room: 7.6 ACH, other rooms average 9.0 ACH.
- A quasi-steady-state observed within 30 min in source room in both experiment and simulation; requires 90 min in other rooms within simulation;
- Ratio of average species concentration within the source room at the inlet diffuser to that in other rooms is **5.0** in the simulation; compared **6.8** in the experiment;
- The quanta generation rate is **14 quanta/h** (G-train);
- **The IP in the source room is location dependent but almost uniform in the other rooms;**
- **Increasing HVAC fresh air proportion to 70% reduces IP by only 18% in the source room but 95% in the other rooms compared with 10% fresh air;**



Fresh air (%)	IP (%) for a 4-hr exposure	
	4 persons in source room	Room 105
10	5.51; 4.00; 2.92; 2.65	0.84
70	4.78; 3.44; 2.23; 1.98	0.045



IMPLICATIONS AND FURTHER DEVELOPMENTS

- ABM can provide insight into the negative impact of physical distancing but usage limited to capacity, through-put and level of service analysis (and proximity dose).
- To understand the potential impact of dispersal of contaminated respiratory aerosols on infection probability within complex spaces it is essential to consider the impact of:
 - Convection currents (e.g. body heat plumes, heating systems)
 - Natural/forced ventilation and its interaction with the spatial configuration.
 - Wake effects caused by walking individuals
 - Requires CFD analysis
- These factors can generate asymmetric dispersal of contaminated aerosols, drive contaminated aerosols in unexpected directions and generate persistent hot-spots, severely impacting the ability of ABM to predict IP and efficacious mitigation strategies.
- Within complex spaces the desirable simplifying assumption of well-mixed environments and hence the appropriateness of simplistic treatments such as WR model for mitigation analysis is questionable and potentially misleading.
 - Simply imposing high ACH may not be a sufficient mitigation strategy
 - HEPA filters alone may not be a sufficient mitigation strategy.
 - Masks can be very effective but requires public buy-in, adherence and education.
 - Partial inoculation and population immunity can be factored into the IP analysis.
- We are currently exploring the development of a new coupling between ABM-CFD (EXODUS-SMARTFIRE) to enable EXODUS predicted agent paths to control the movement of agents within SMARTFIRE.

