

Air Ventilation & Purification in Buses and Coaches to prevent the spread of viruses

A Research Project of Busworld Foundation, and supported by



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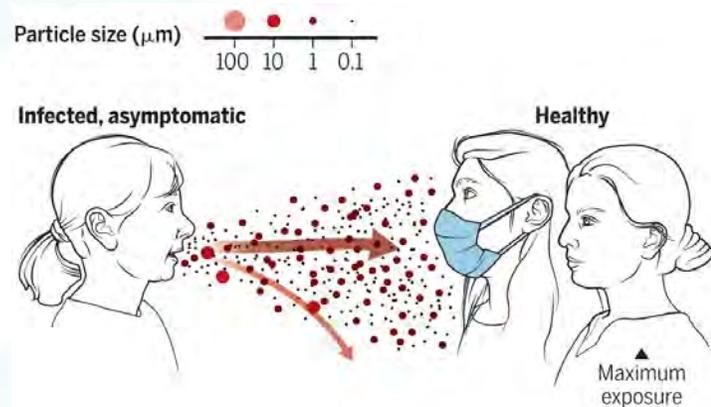
BUSWORLD foundation

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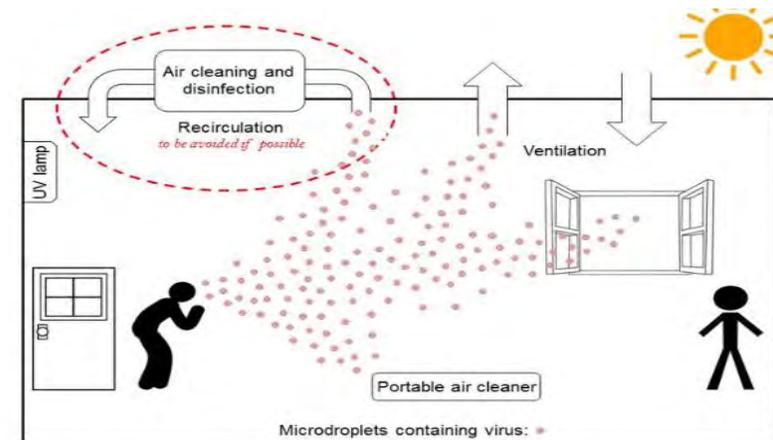
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Airborne transmission of viruses

- Transmission via microdroplets containing virus
- Emitted by infected individual during breathing, speaking, coughing, sneezing ...
- Large droplets fall down, small droplets can stay airborne (aerosols)
- Cross-infection risk of aerosols decreased via effective ventilation



Release of infectious microdroplet particles



Engineering level control to reduce environmental risks for airborne transmission of COVID-19 [2]

[1] Prather K., Wang C., Schooley R., Reducing transmission of SARS-COV-2, American Association for the Advancement of Science, 2020, ISSN 1095-9203

[2] Lidia Morawska *et al.*, How can airborne transmission of COVID-19 indoors be minimised?, Environment International, Volume 142, 2020, 105832, ISSN 0160-4120

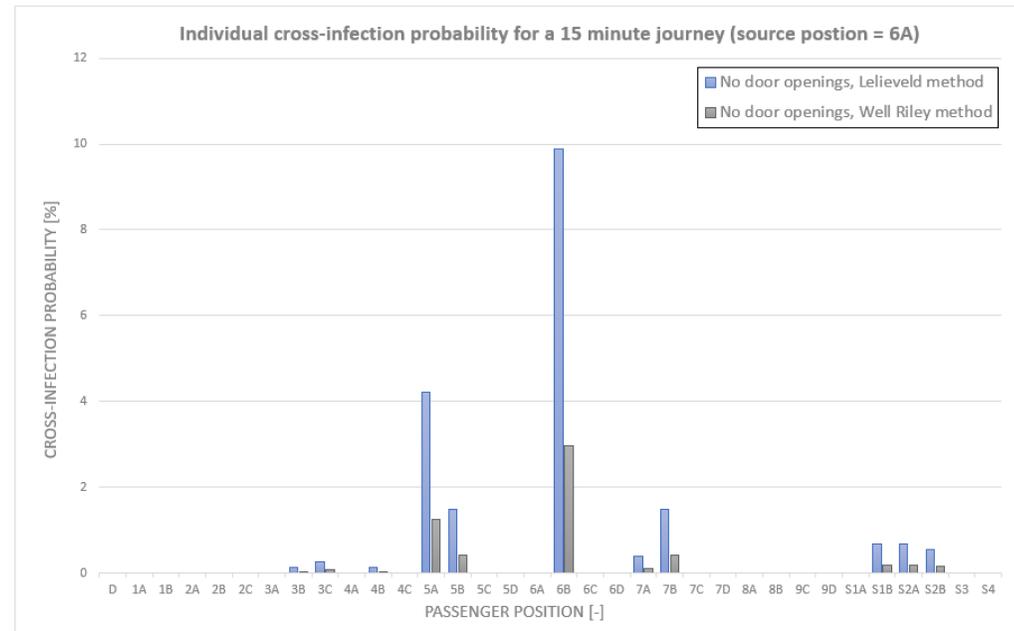
AIR VENTILATION

Cross-infection risk calculation method: comparison

LELIEVELD vs WELLS RILEY (adapted by ZHY)

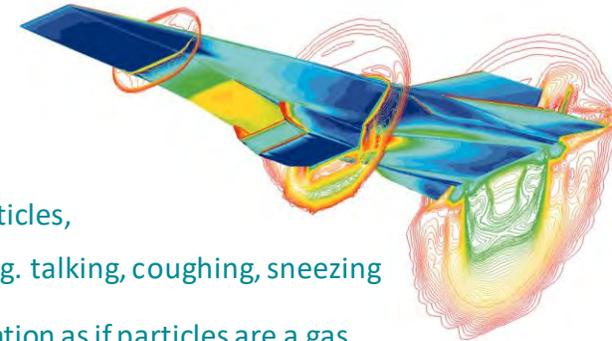
- Both methods result in qualitatively very similar cross-infection risks.
- The method from Lelieveld *et al.* results in higher absolute cross-infection risk.
- Difference is thus likely related to the values of the input parameters (emission rate and infectiousness). However, these values are uncertain at this stage of the pandemic.

The more conservative results from the Lelieveld method are used.

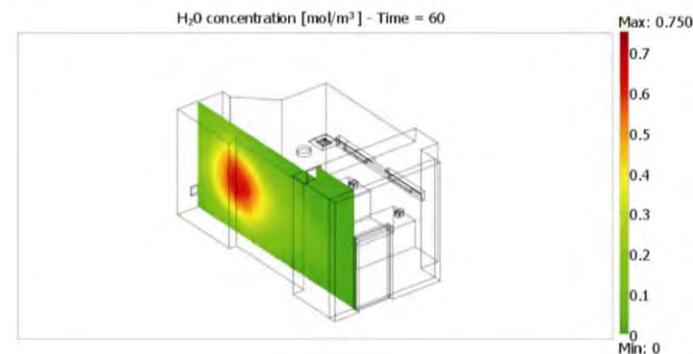
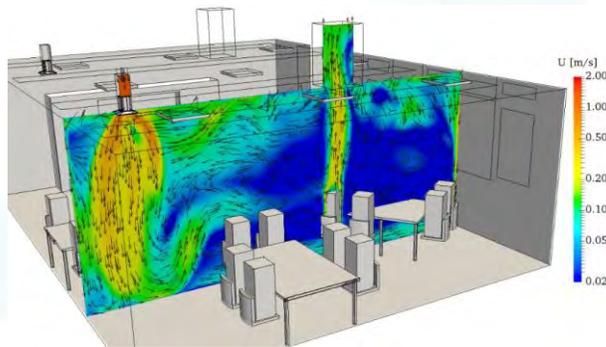


Modelling

- Computational Fluid Dynamics (CFD)
- Discrete Phase Modelling : Modelling technique that calculates the trajectory of particles, based on the forces exerted by gravity and the flow field, More appropriate for larger particle sizes e.g. talking, coughing, sneezing
- Drift-Flux Particle Model : Modelling technique that calculates the particle concentration as if particles are a gas, No explicit 'dropping to the floor' but still deposition onto surfaces, More appropriate for smaller particle sizes e.g. breathing

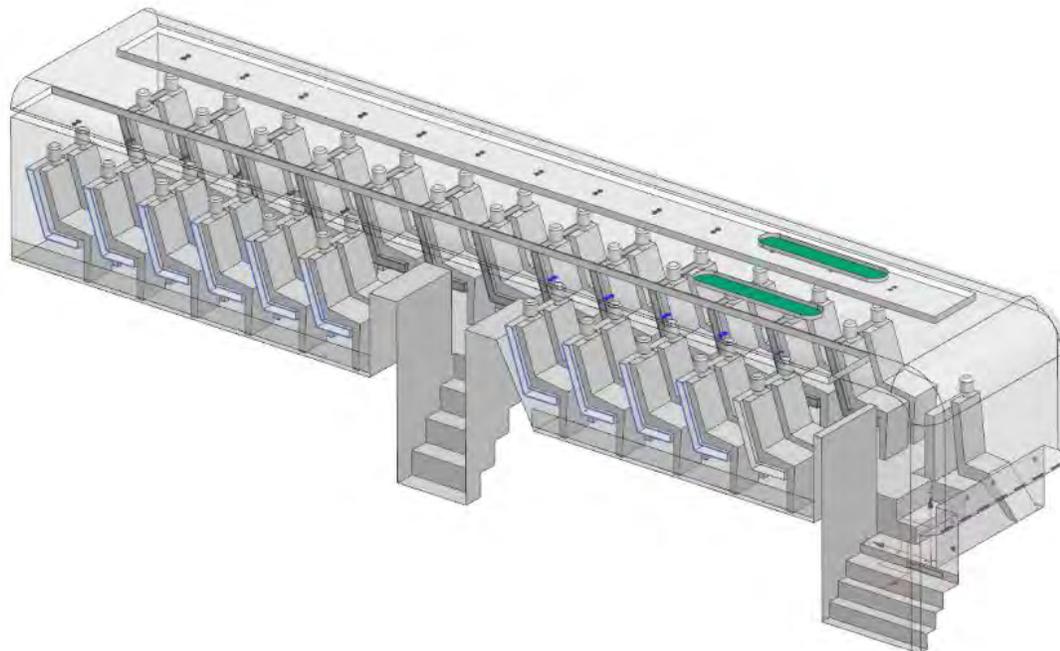


Both able to calculate & visualize spread of microdroplets emitted by infected individual within the bus
Evaluate ventilation effectiveness, droplet hot-spot identification, estimation of infection risk.



THE COACH CASE

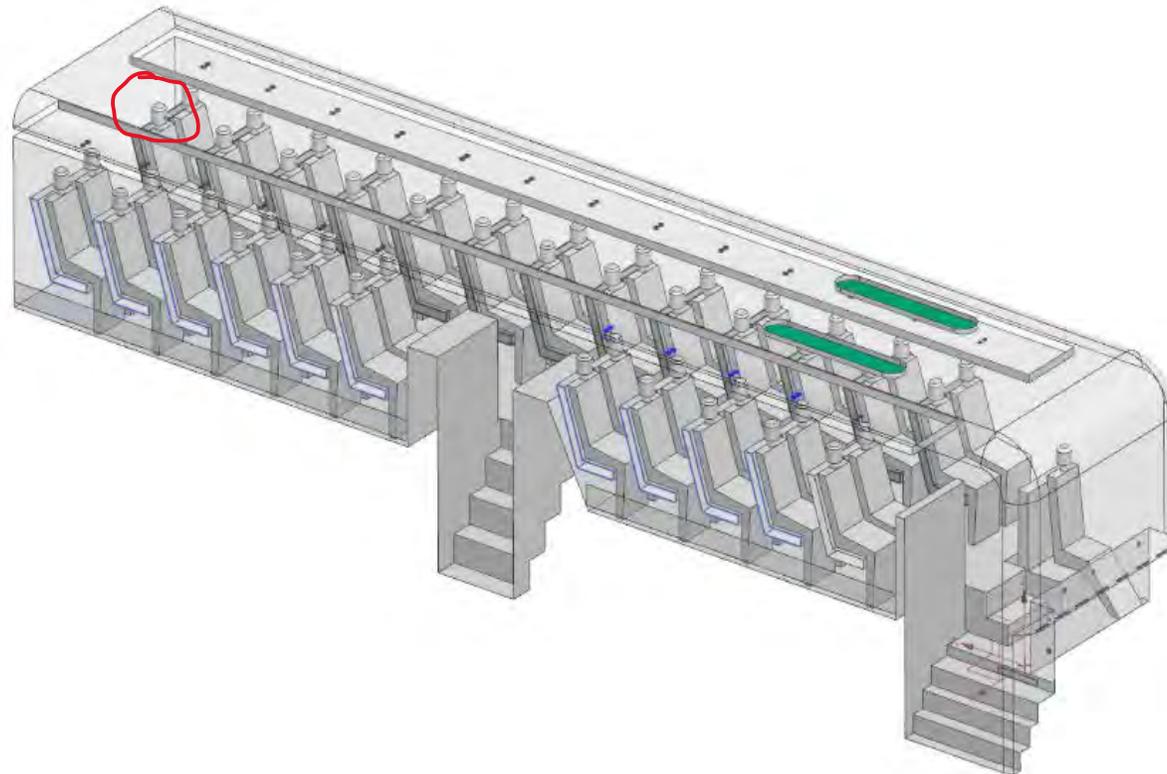
Evaluation of particle distribution within a 12m coach



- **Assumptions & variables**

- Ventilation flow rates: $900 \text{ m}^3/\text{h}$ (17.2 ACPH); $1625 \text{ m}^3/\text{h}$ (31 ACPH); $3000 \text{ m}^3/\text{h}$ (57.4 ACPH)
- Coach at full capacity
- Aerosol free air supply (fresh air, 100% filter efficiency)
- Breathing/speaking at typical indoor conditions: 170 airborne droplets per second [3]
- Droplet size = $1\mu\text{m}$ (non-volatile droplet nuclei)
- Evaporation not explicitly modelled (standard indoor relative humidity)
- No biological degradation while virus is airborne (virus half-life about 1.15h [3])
- Deposition on surfaces

Base Ventilation Layout



CROSS INFECTION RISK

- Allows for a quantitative evaluation of particle spread
- Methodology adapted from Lelieveld et al. [3] (see appendix)

$$P_i = [1 - (1 - P_{RNA})^{D_{ep}}]$$

P_{RNA} the infection risk from 1 viral copy

D_{ep} the number of inhaled viral copies

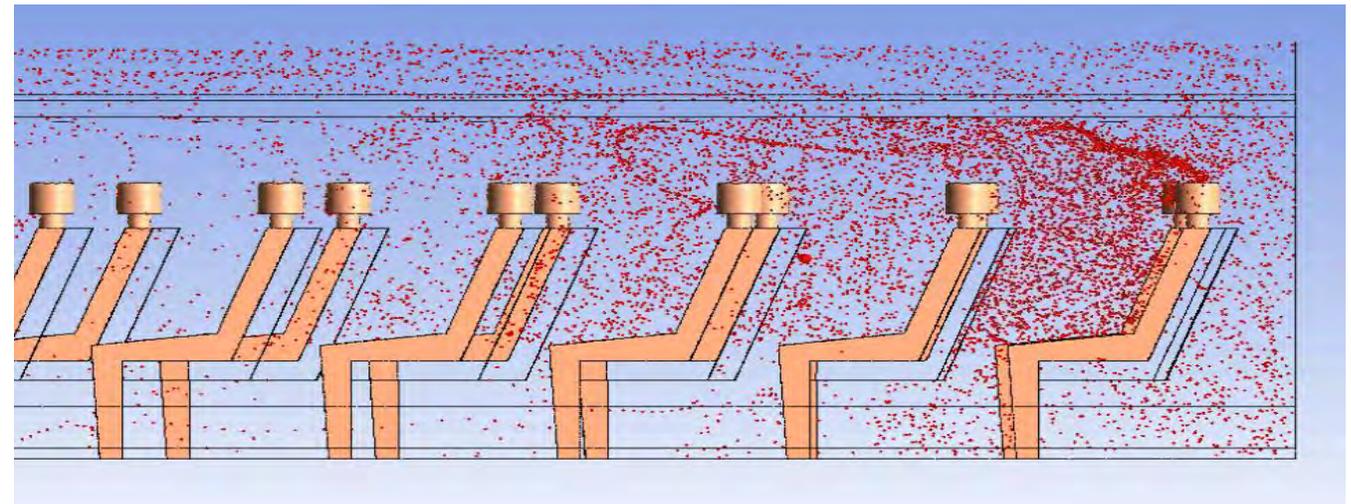
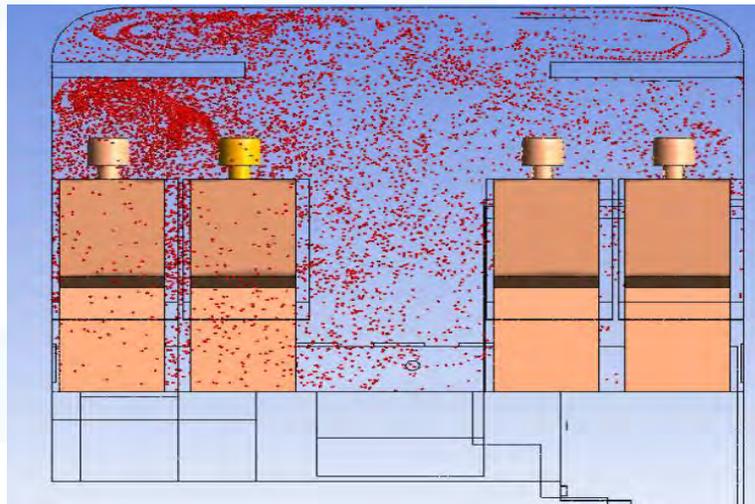
- Source patient at position 13B (worst case scenario) or 6B (cross-infection risk = 0%)

Base Layout – 900 m³ /h

- Largest fraction of particles in front/above the head of the individual seated next to the source patient
- High concentration in between source and back of next seat
- Small fraction of particles travels towards the extraction vent (<10%) (in line with other similar studies [4])
- Significant backward spread of particles

Particle Faith Fractions [-]	
Trapped	0.912
Escaped	0.088
Incomplete	0

Particle Residence Time [s]	
Average	59.40
Maximum	345.50



Base Layout – $1625m^3/h$ – 13B

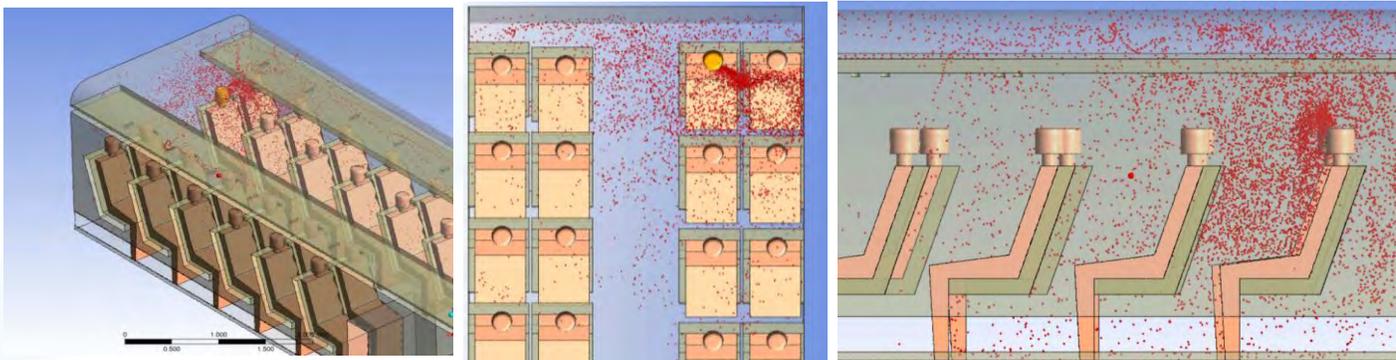
- Similar concentration field as for lower flow rate:
highest concentration in front/above source patient and adjacent person
- Lower spread of particles towards the front of the coach
- Even smaller fraction of particles travels towards the extraction vent (<3%)
- Lower average and maximum particle residence times

Particle Faith Fractions [-]

Trapped	0.975
Escaped	0.025
Incomplete	0

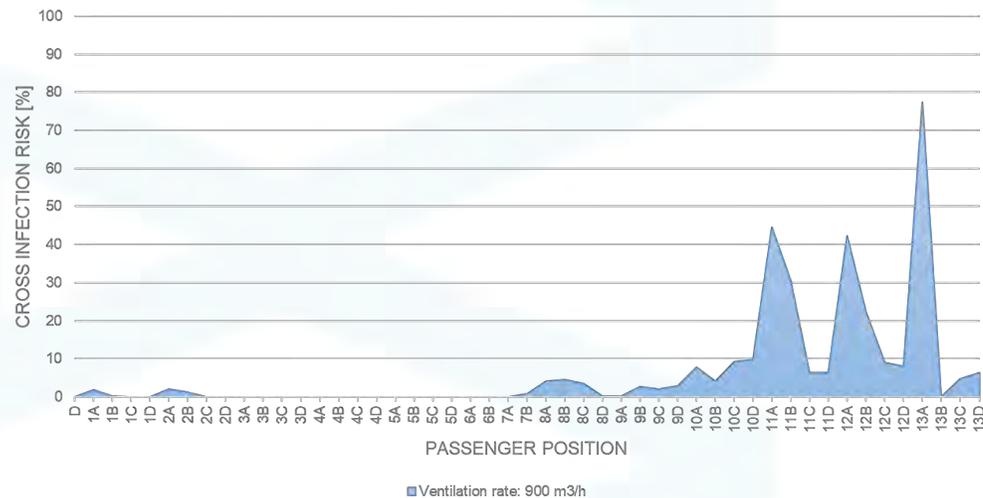
Particle Residence Time [s]

Average	45.86
Maximum	276.94

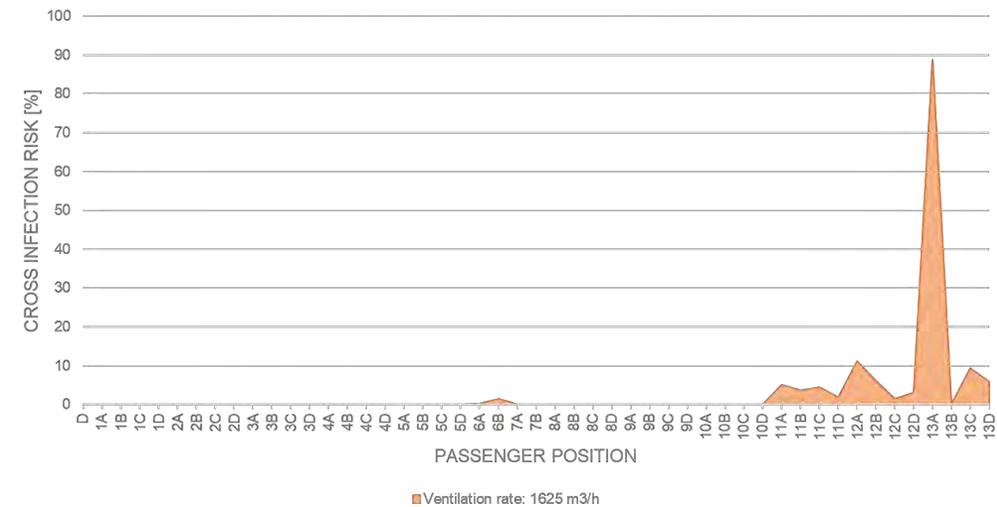


Cross infection risk vs Ventilation rate

Individual cross infection risk for a 2h journey as a function of location for the base ventilation layout with source at position 13B



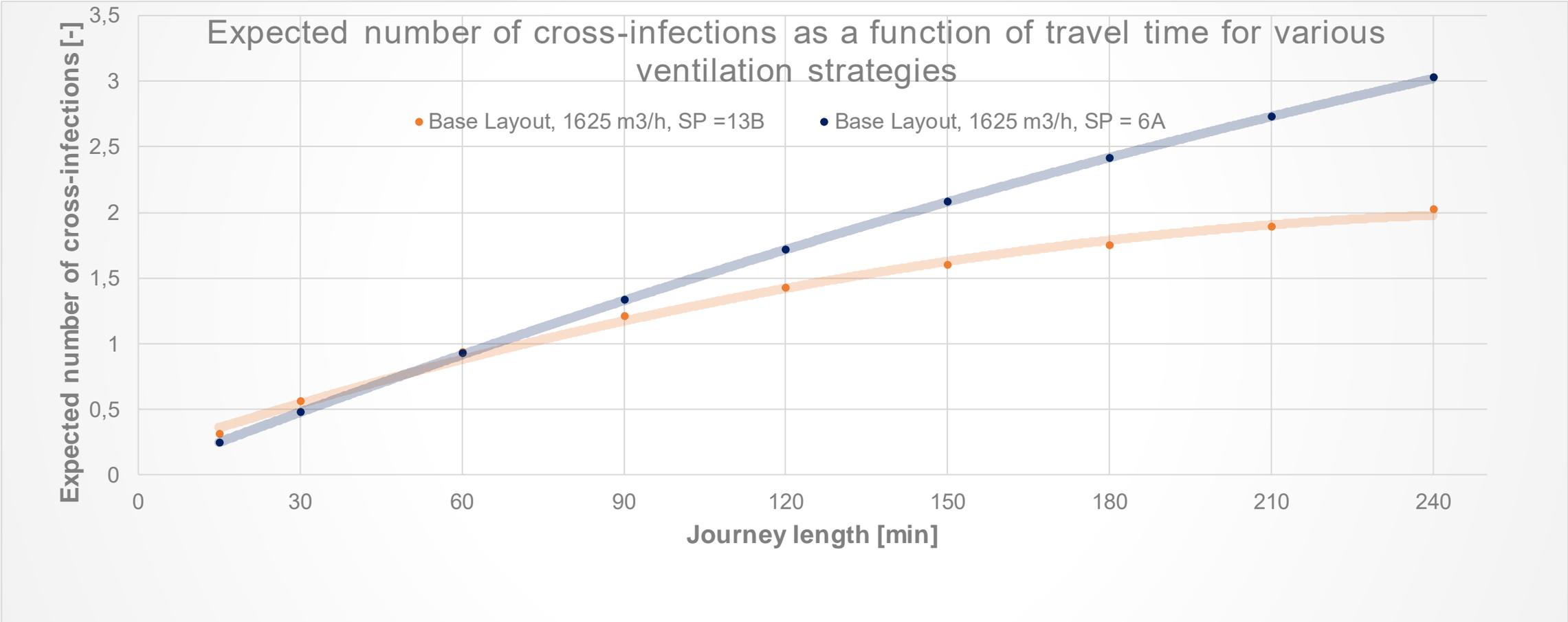
Individual cross infection risk for a 2h journey as a function of location for the base ventilation layout with source at position 13B



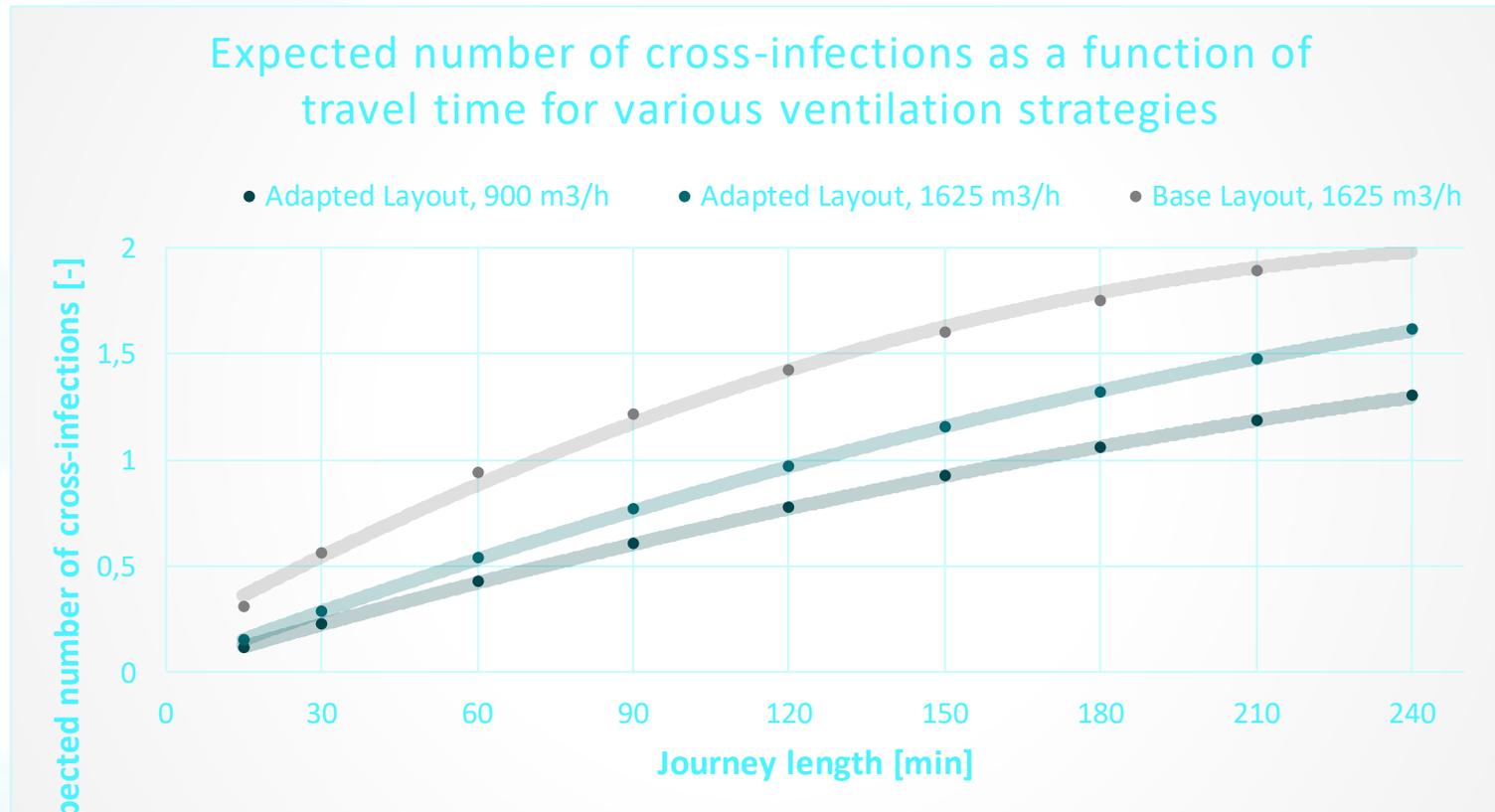
At higher flow rate, particles concentration near source is higher due to stronger recirculation zones:

- Higher local cross infection risk for higher flow rate
- Higher overall cross-infection risk for lower flow rate

Cross infections vs Source position



Expected number of cross infections

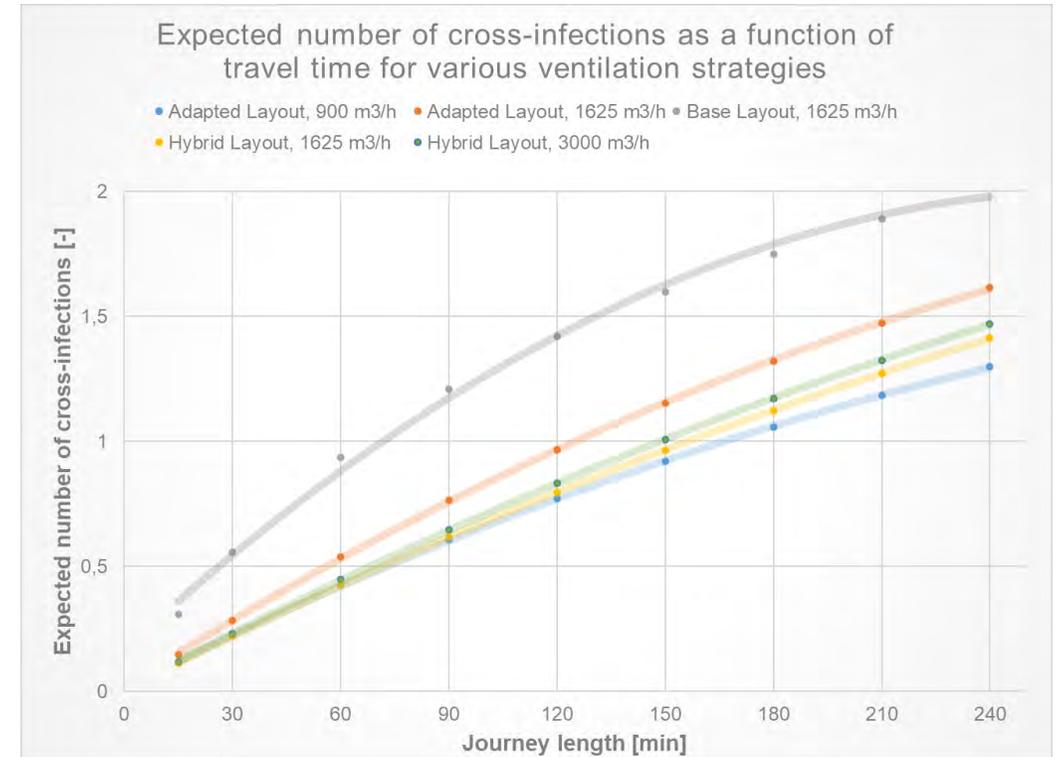


Adapted ventilation superior to base layout due to decreased pull towards the front of the bus. Lower flow rate performs slightly better

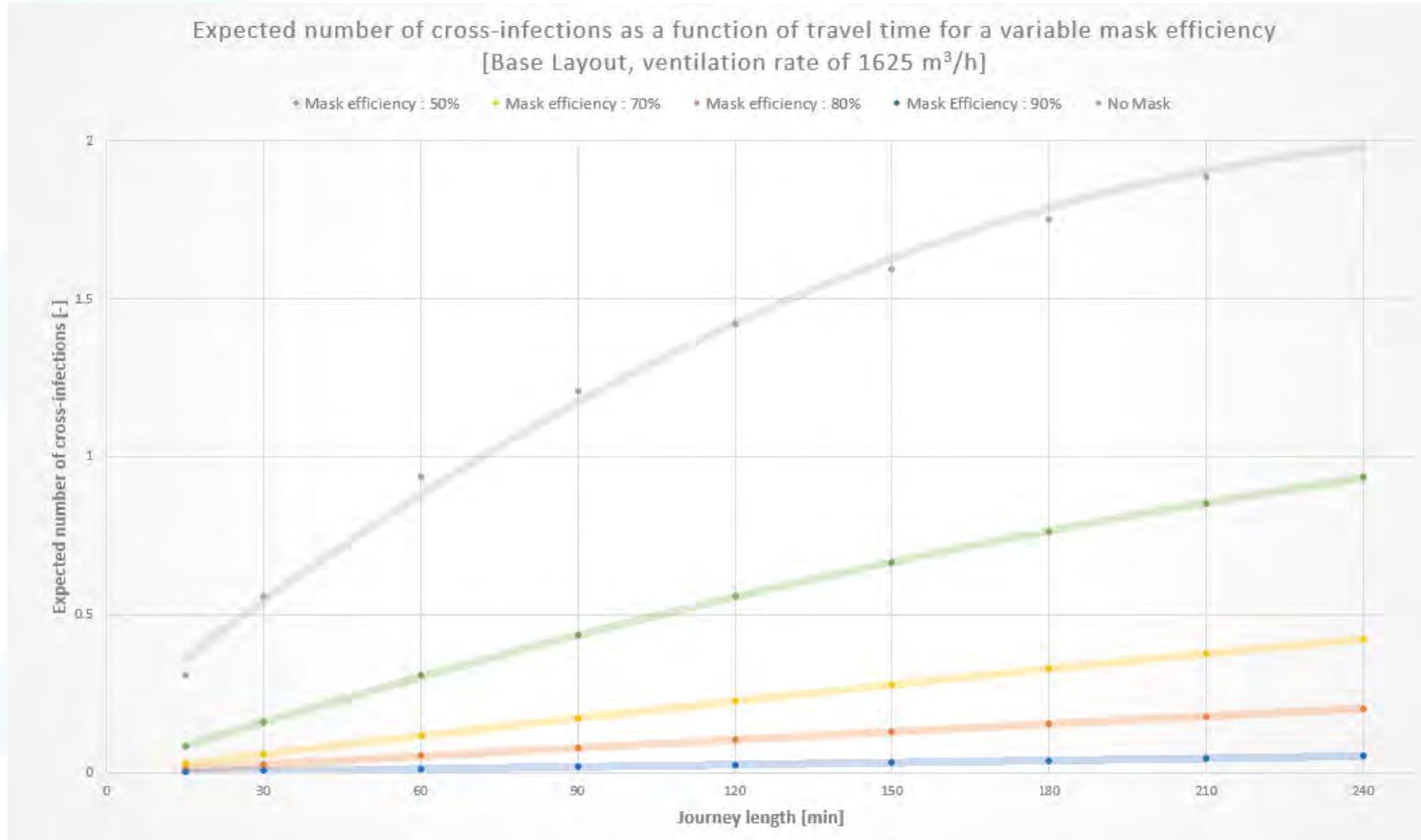
Conclusion

Position 13B

- Base adapted and hybrid ventilation configurations result in similar concentration fields since local flow field near source is almost identical
- Higher flow rates and stronger recirculation zones cause larger deposition rates
- Only a small fraction of particles is actually extracted
- Usage of highquality masks can significantly decrease expected number of cross infections



Mask efficiency

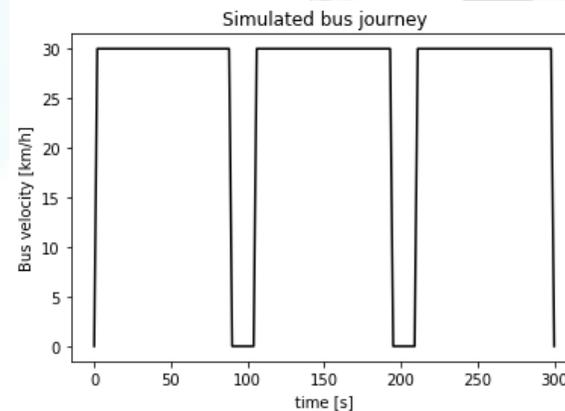
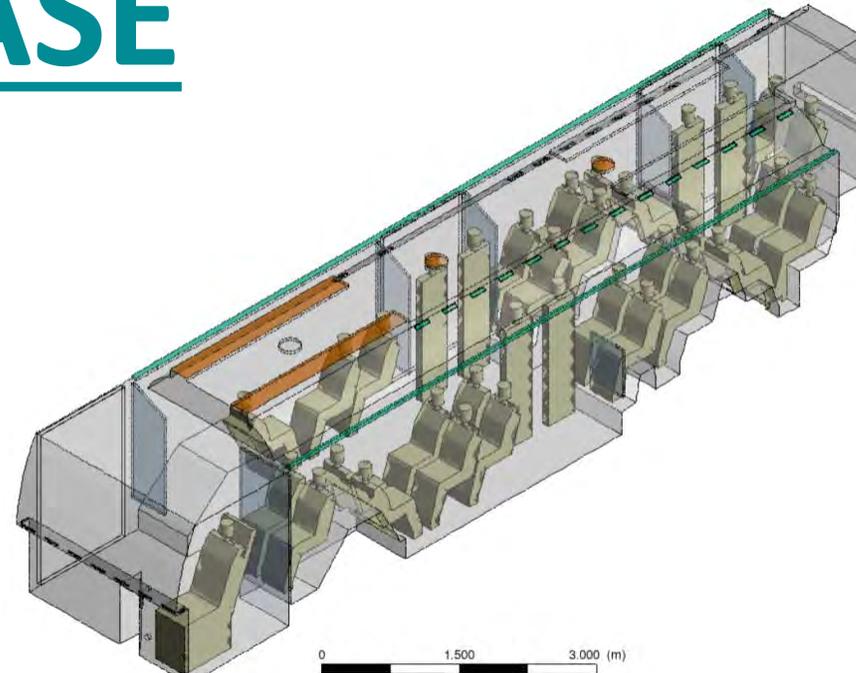


Correct usage of masks significantly decreases cross infections risks

The BUS CASE

Assumptions

- Maximum ventilation rates
- Full re-circulation mode
- Aerosol tracked using a DPM model:
170 airborne droplets per second,
1 μ m diameter
- Source position varied between: 6A,
1B, 7D and S2B



- Travel time between stops of 90s
- Door opening time of 15s
- Two door openings simulated
- Door boundary condition: stationary
0 Pa (no wind)

THE BUS CASE

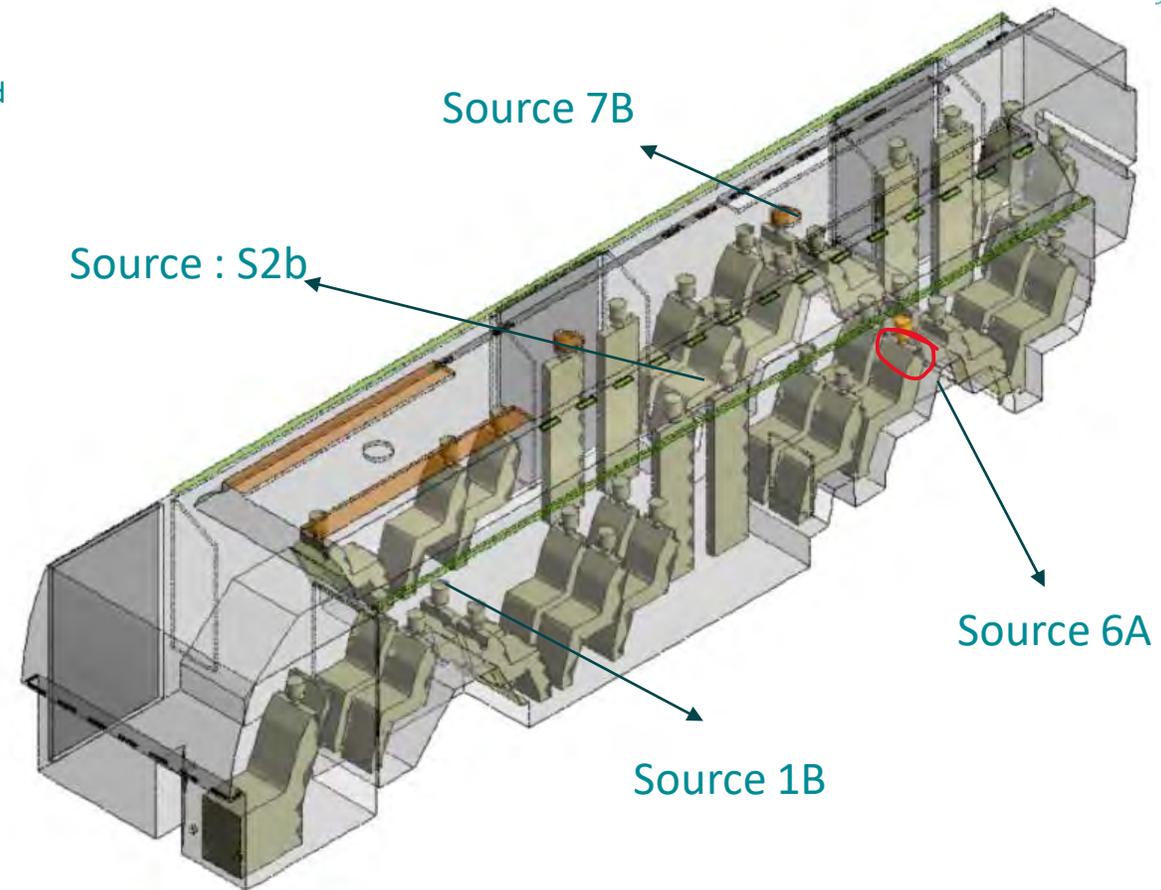
Geometry and Ventilation system : Detailed information from geometry and ventilation system for VDL Citea SLF120

Passenger zone (practical max of 1620 m³/h):

- Window supply vents (15%)
- Aisle roof supply vents (85%)
- Recirculation extraction vents
- Overpressure extraction vents (30Pa)

Driver zone (600 m³/h) :

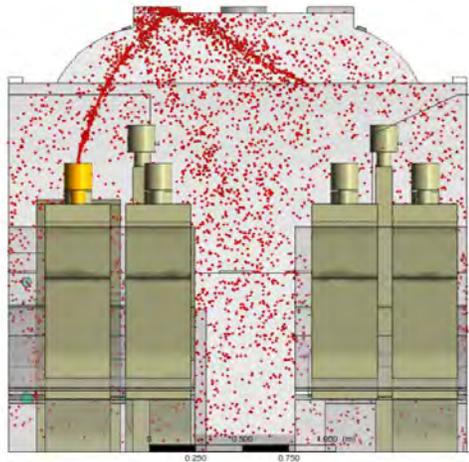
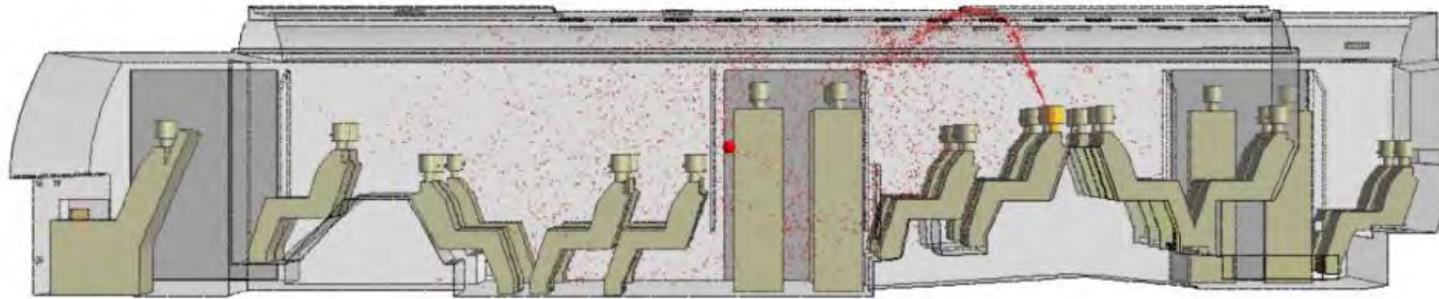
- Dashboard supply vents
- Feet supply vents
- Windshield supply vents
- Recirculation extraction vent



First results (Steady State) – 6A

Steady state (no door openings) - Driver air supply: 600 m³/h - Passenger air supply: 1620 m³/h

Source at position **6A** - Particles: 170 per second, 1µm



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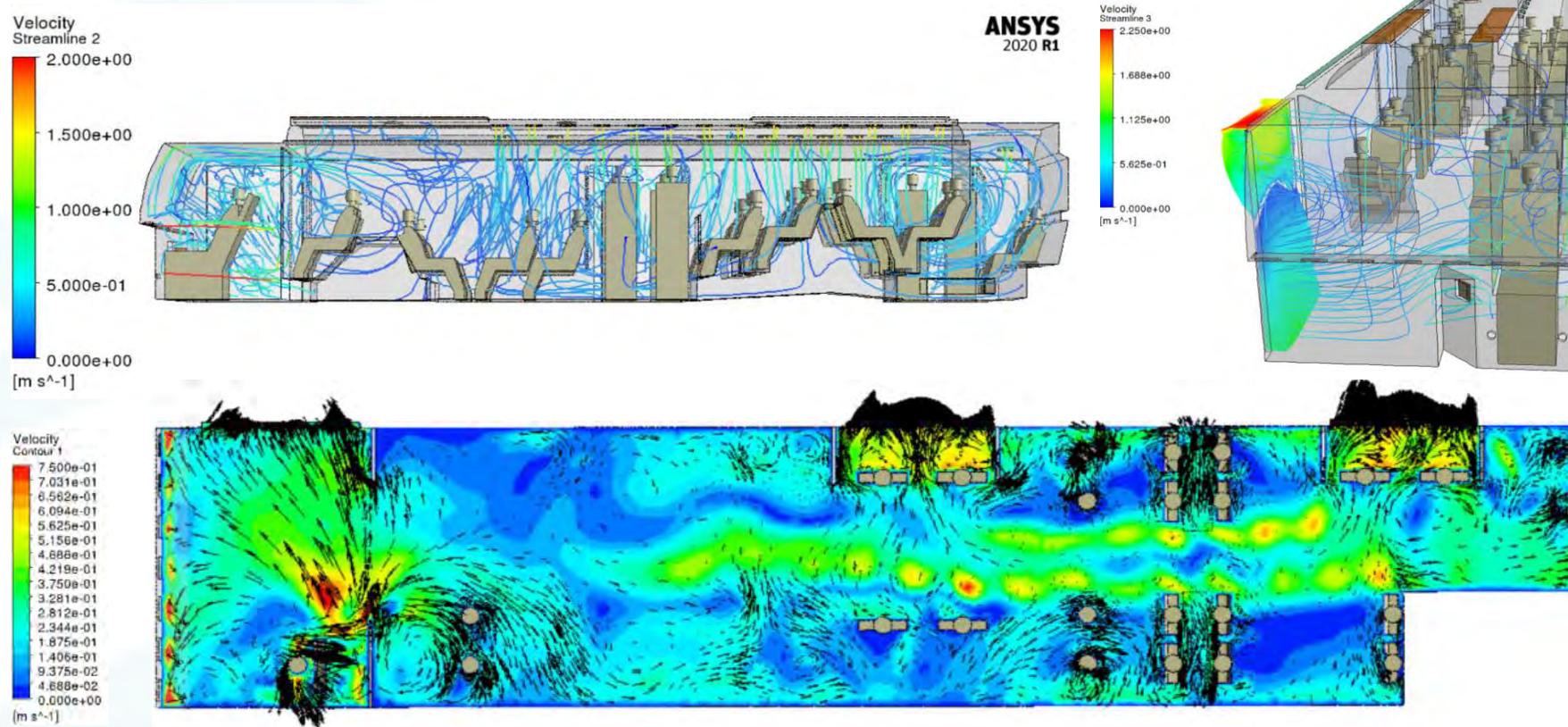


- Upwards motion near source
- Particles spread towards front of the bus
- Only 14% of particles are extracted
- 80% of particles are deposited on surfaces

Particle Faith	Fraction [%]
Extraction	14
Deposited	80.7
Suspended	5.3

Flow through the doors

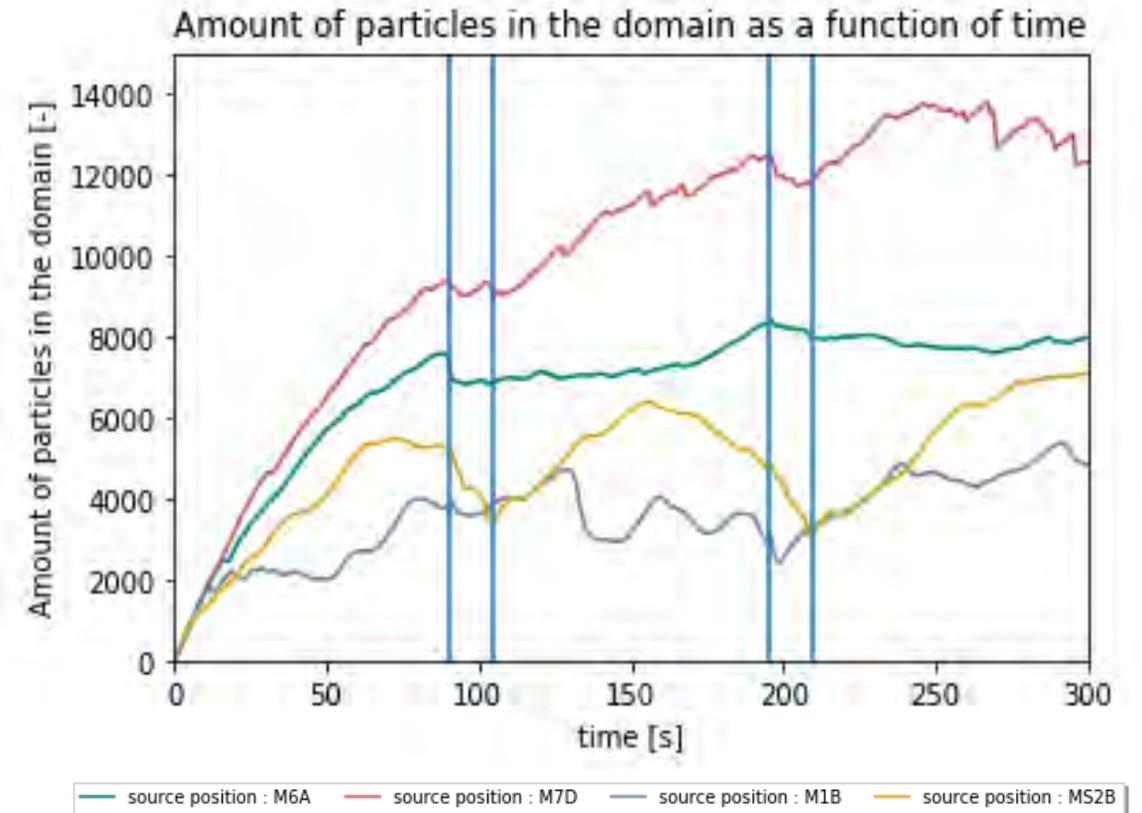
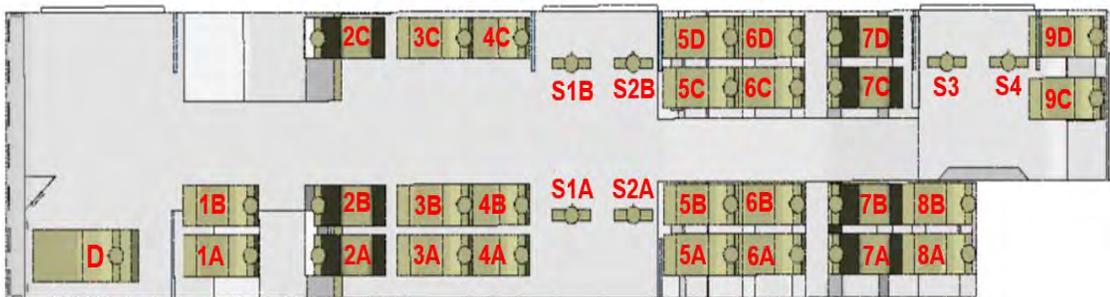
10 sec after door opening



Normal ventilation system remains operational. As such, the flow field is not affected by the door openings. Flow goes out at the top of the doors and comes in at the bottom. Overall flow field is slightly rearwards

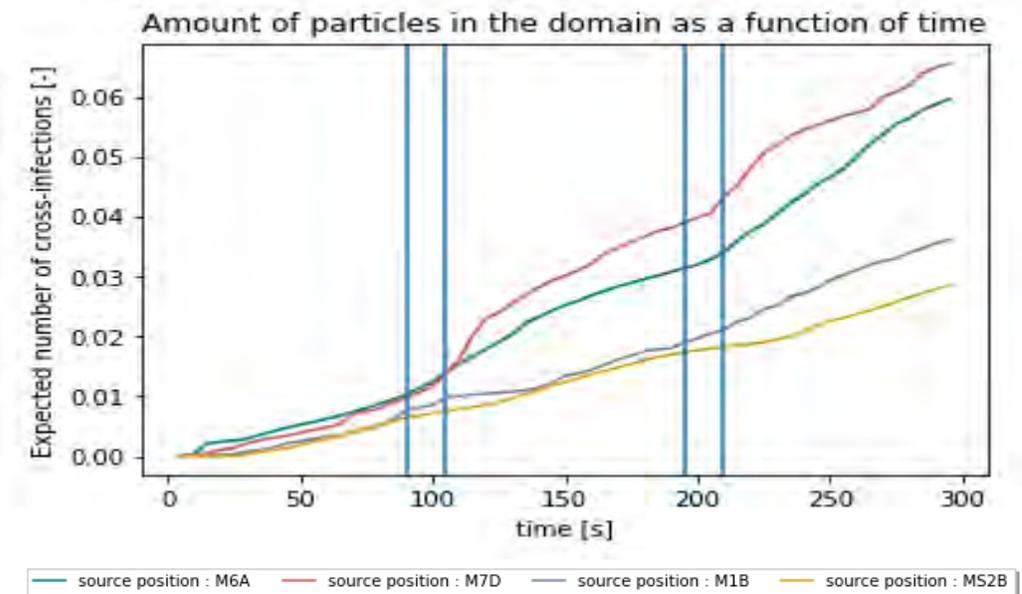
Comparison source positions for concentration of aerosols

- Overall concentration of aerosols the highest for source located at position 7D. Lowest for source at 1B



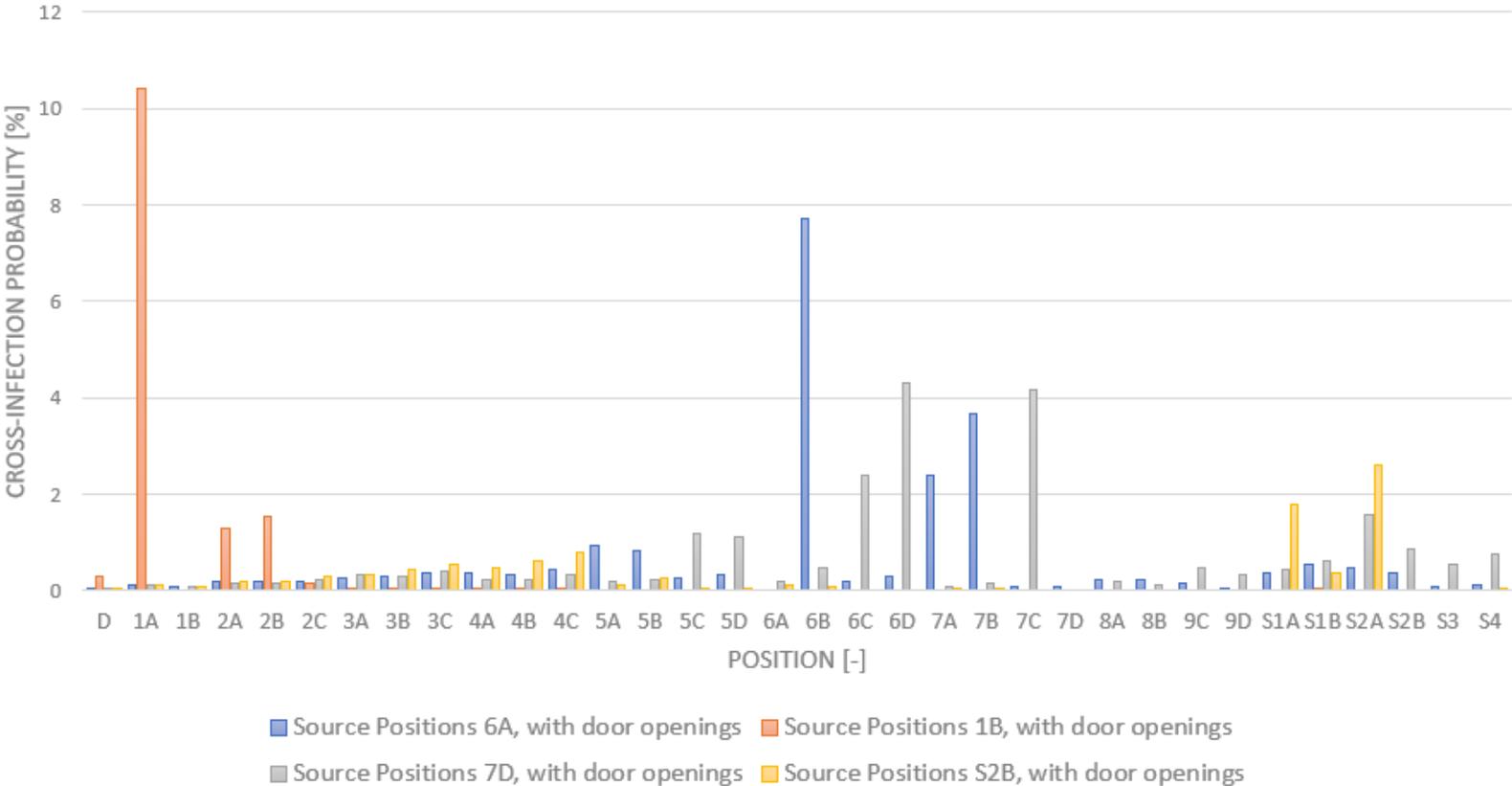
Comparison Source Positions Expected number of cross-infections

- Highest expected number of cross-infections if the source is seated nearer to the back of the bus
- Standing source leads to the lowest amount of expected number of cross-infections (likely due to door openings)



Comparison Source positions Individual cross-infection risk

Individual cross-infection probability for a 15 minute journey



AIR PURIFICATION

Objective

- To review the available air filtration system in the market
- To develop basic criteria to evaluate the best products available
- To evaluate the air filtration systems using basic criteria.

Criteria

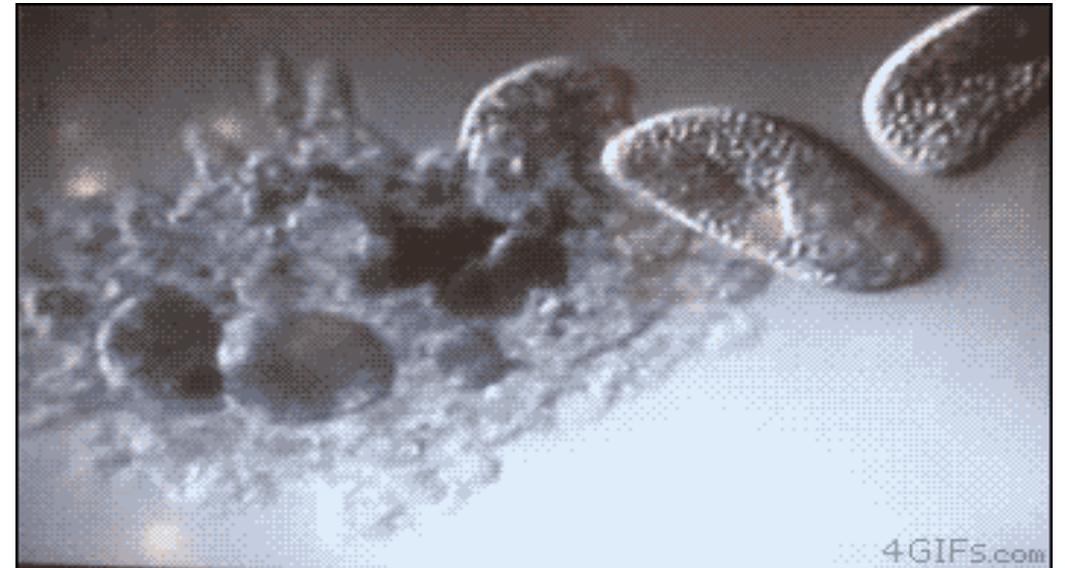
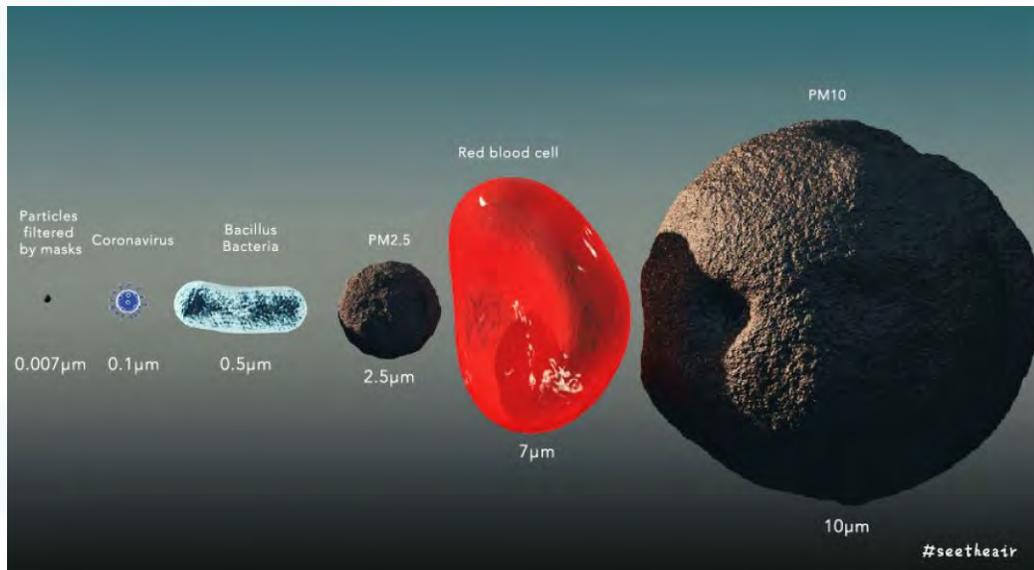
- ✓ Effect on Viruses & bacteria
- ✓ Tested against Sars-cov2 (COVID-19)
- ✓ Use in the presence of people
- ✓ Toxicity
- ✓ Health hazards
- ✓ Operating cost or Energy consumption
- ✓ Performance
- ✓ Maintenance
- ✓ Disposables
- ✓ Speed of effectiveness
- ✓ Authorizes use for COVID- 19

Technics being evaluated

1. Ionisation
2. Ozone based
3. UV-light based
4. Photocatalysis
5. Hypochlorous acid
6. HEPA filters

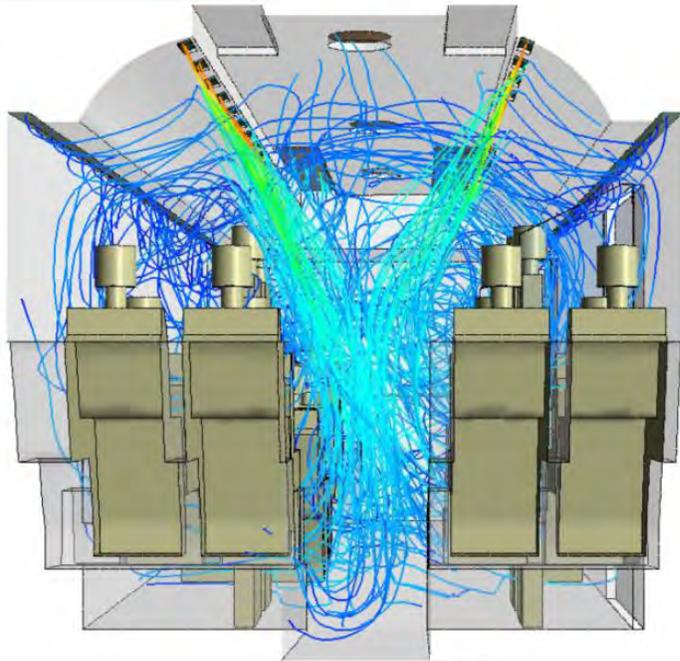
Contact us to join in this program

- Jan.Deman@busworld.org

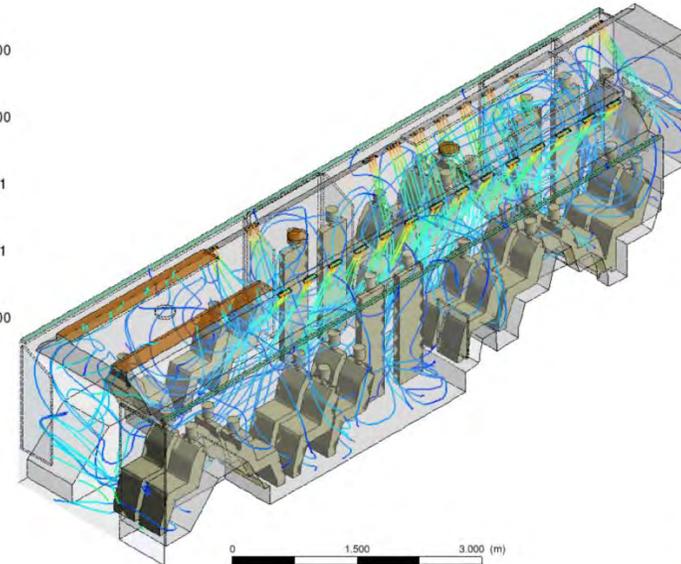


Passenger zone flow field

Velocity
Streamline 2
1.750e+00
1.312e+00
8.750e-01
4.375e-01
0.000e+00
[m s⁻¹]

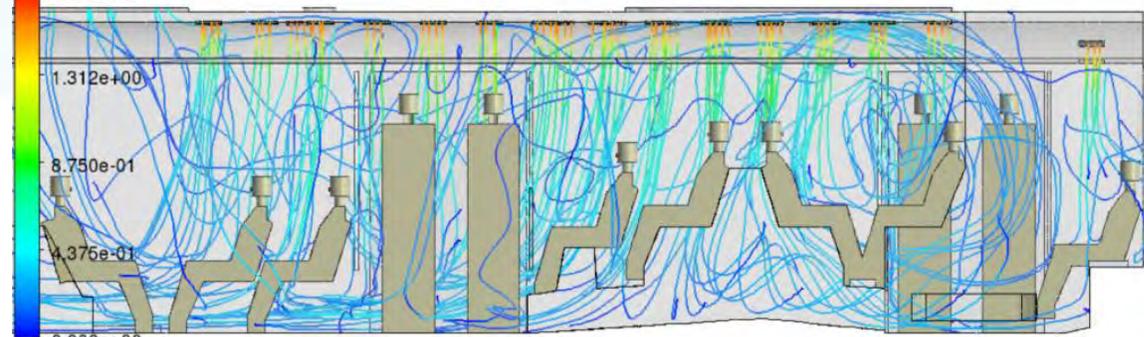


Velocity
Streamline 1
1.750e+00
1.312e+00
8.750e-01
4.375e-01
0.000e+00
[m s⁻¹]



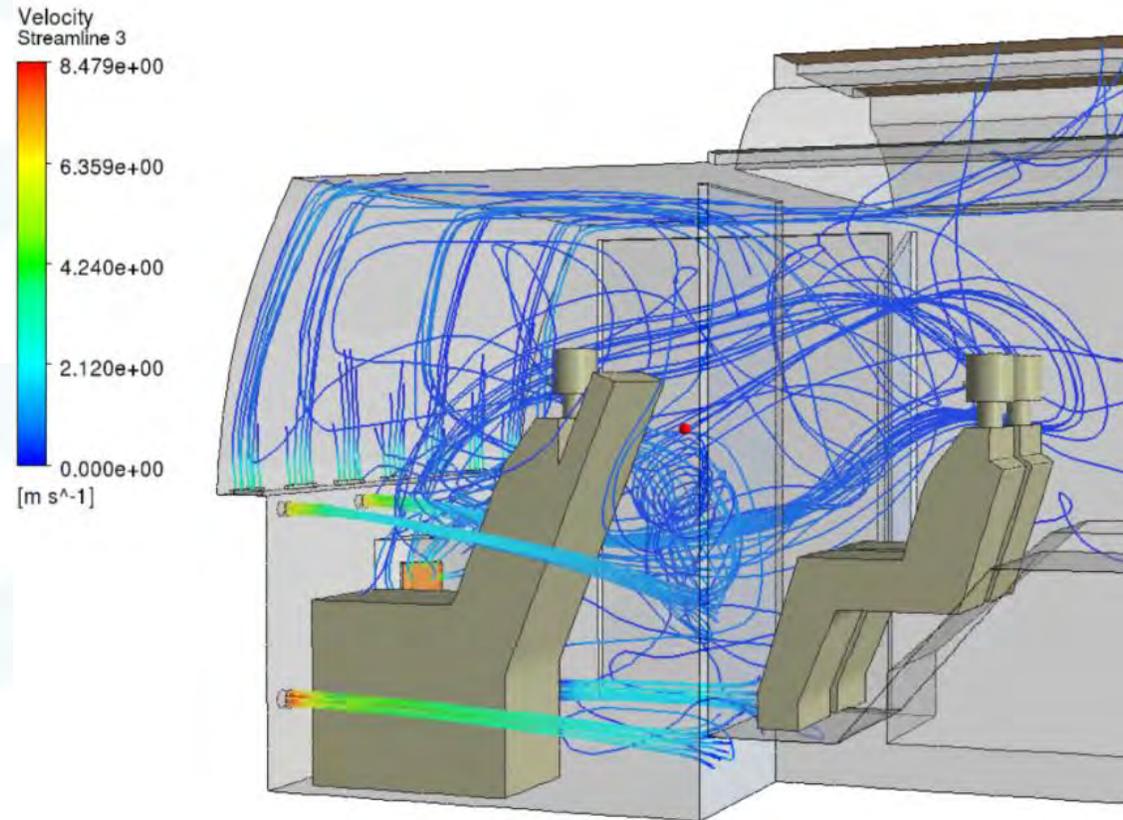
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Velocity
Streamline 1
1.750e+00
1.312e+00
8.750e-01
4.375e-01
0.000e+00
[m s⁻¹]



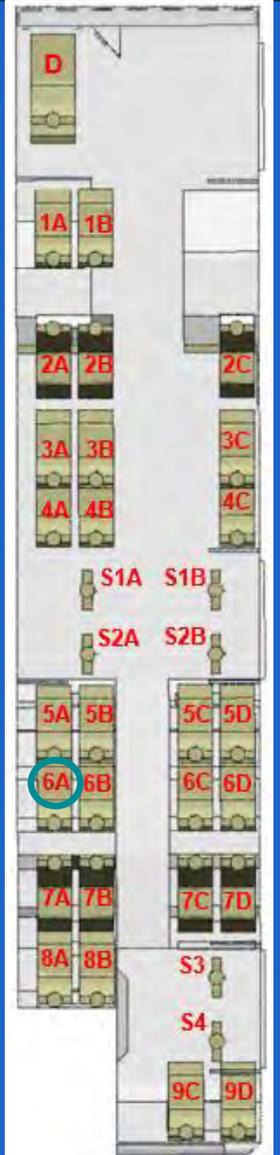
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Driver Cabin Flow field



The BUS CASE - with door openings

Source position 6A

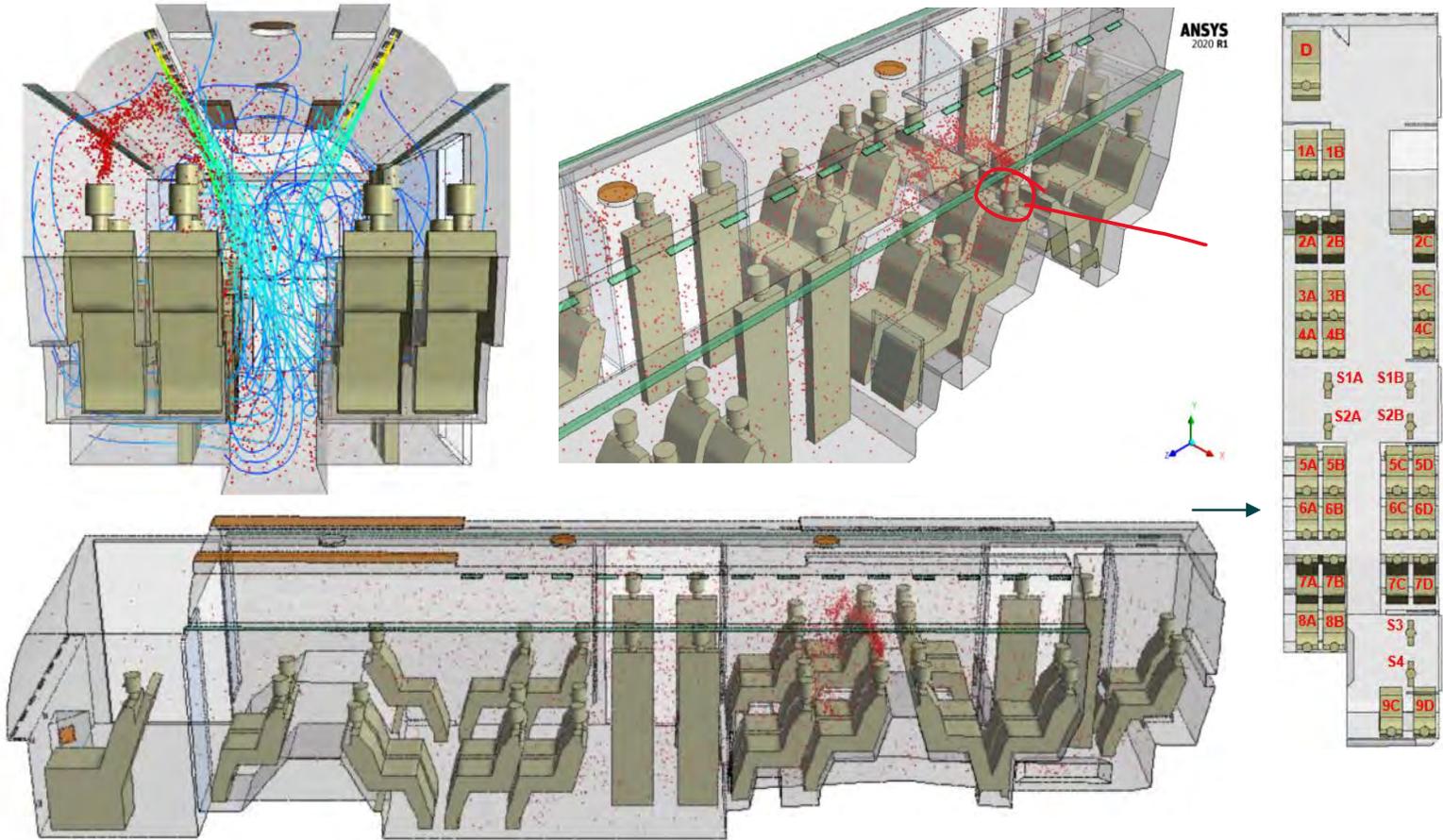


Aerosol distribution – Source 6A

- Particles forced upwards by the swirling flow of the roof inlets
- Aerosols disperse over the entire bus
- About 20% of particles is extracted by the ventilation system

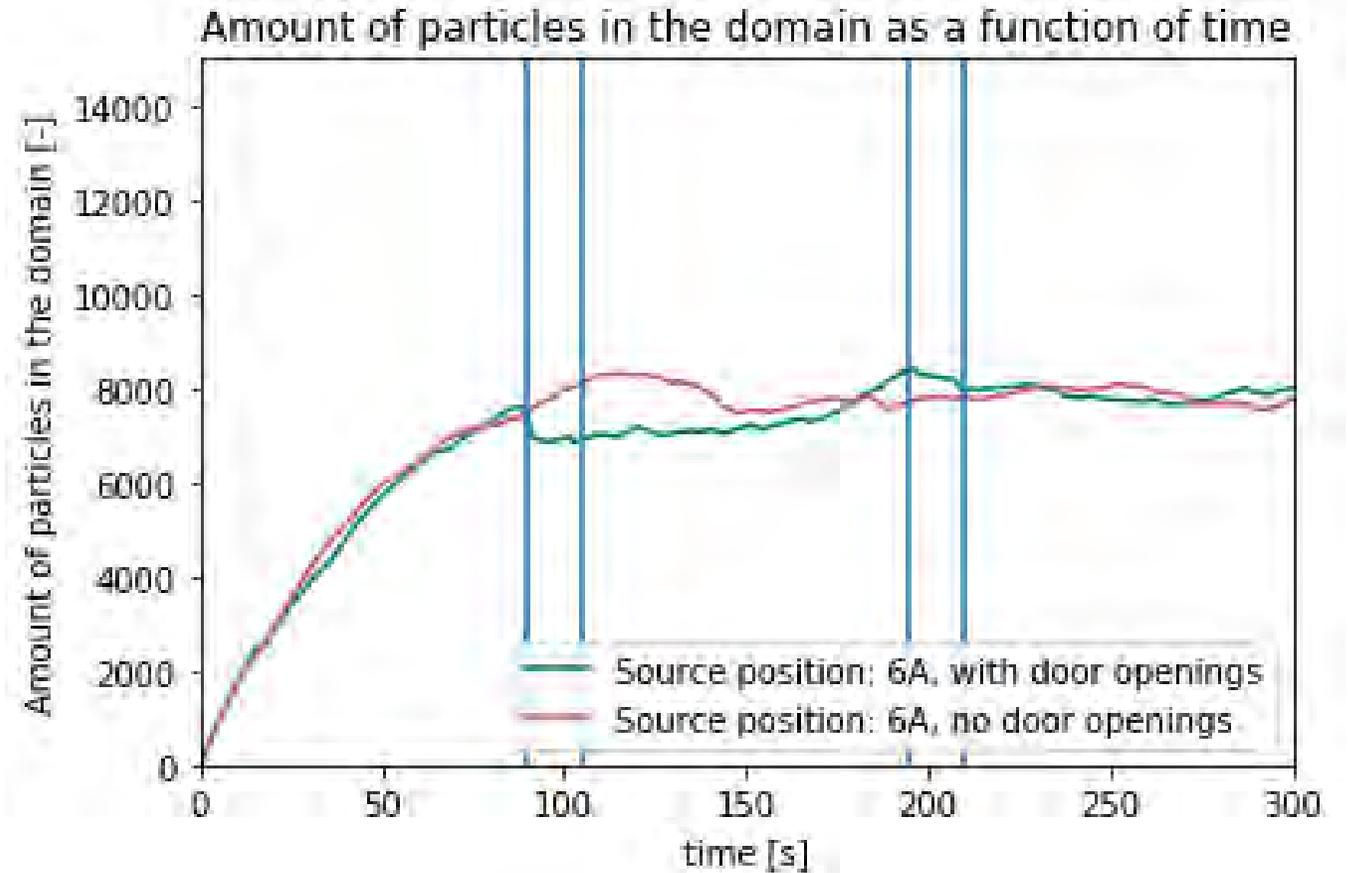
Particle faith fractions on end of simulation time [-]

Deposited	0.654
Extracted	0.191
Suspended	0.155



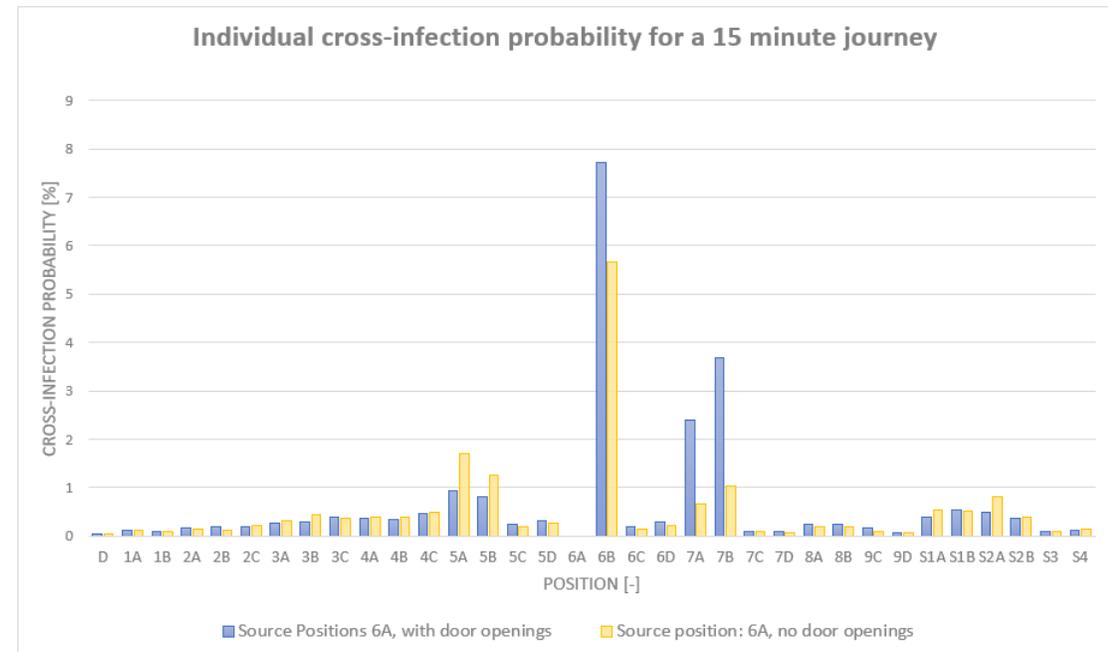
Aerosol concentration over time – 6A

- Amount of aerosols in the bus stabilizes within a few minutes
- When the doors are closed, the bus is at a slight overpressure
→ drop in aerosols directly upon opening the doors
- Door openings have no clear impact on the overall aerosol level in steady state conditions.



Cross-infection probability – 6A

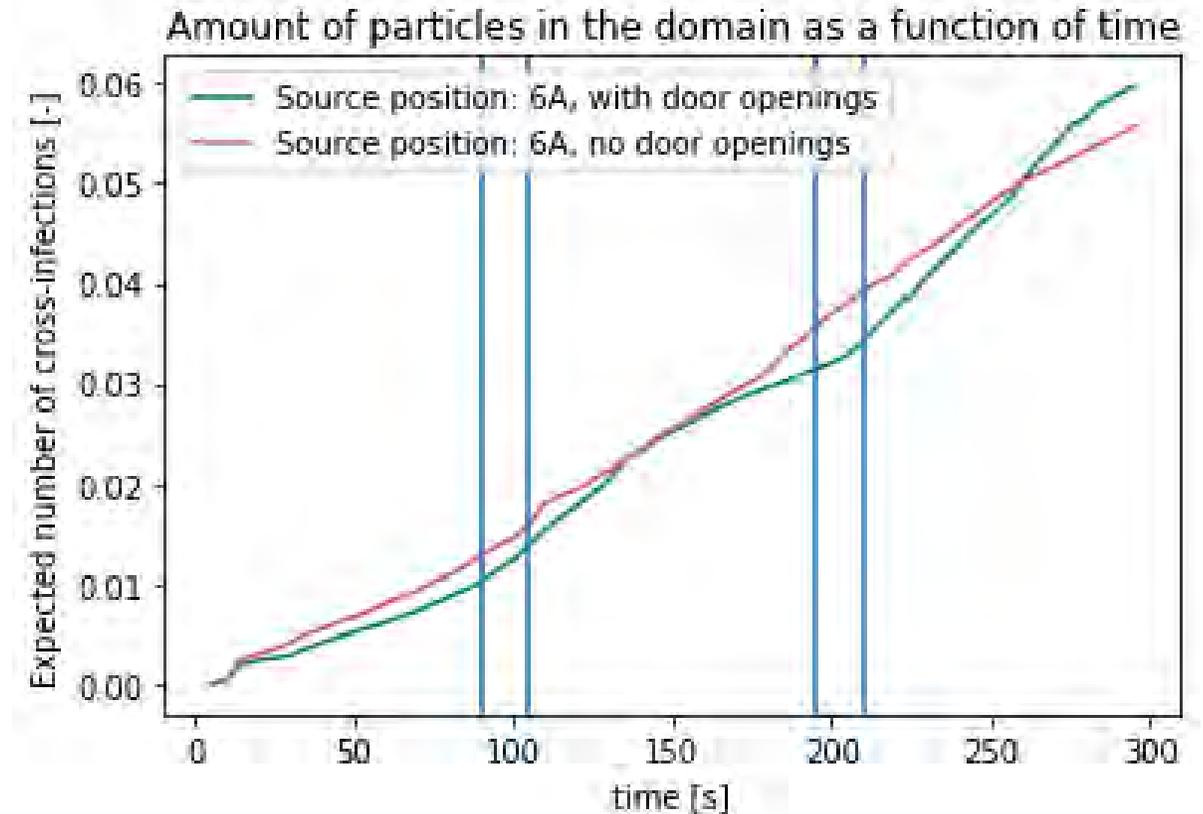
- Source at position 6A
(infection risk for source not considered)
- Cross-infection only due to inhalation of infected aerosols
- 15 minute journey. Longer journeys will lead to a higher cross-infection risk
- Highest cross-infection risk for the adjacent passenger but is still low: around 8% with door openings
- Wide dispersion of the particles means that there is a cross-infection risk for nearly every passenger on the bus.
→ 1.5m social distance is not sufficient
- Door opening does not lead to a clear improvement



Disclaimer: the cross-infection risk are an estimation and are subject to a relatively large degree of uncertainty.
Use with care

Effect of door openings on cross-infection risk – 6A

- Expected number of cross-infections as a function of time **up to 300s**
- Door openings do not have a large effect on the slope of the expected number of cross-infections. This is in line with the estimation of Zhang [2]



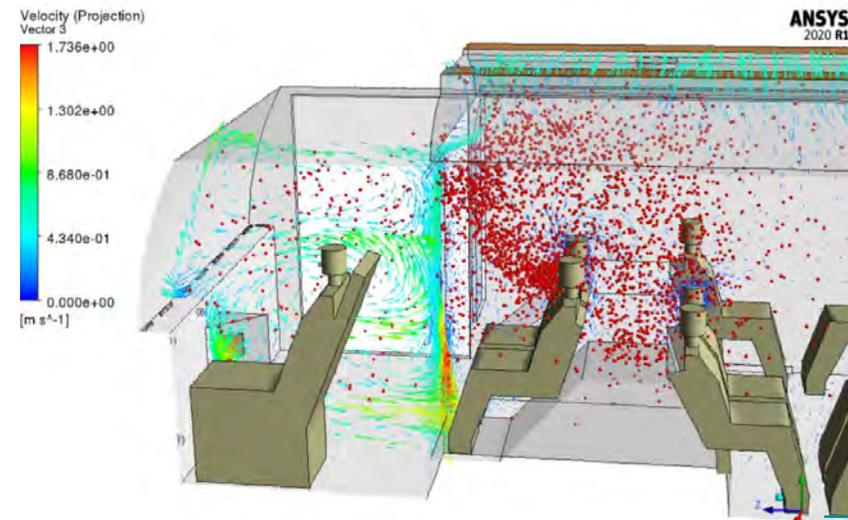
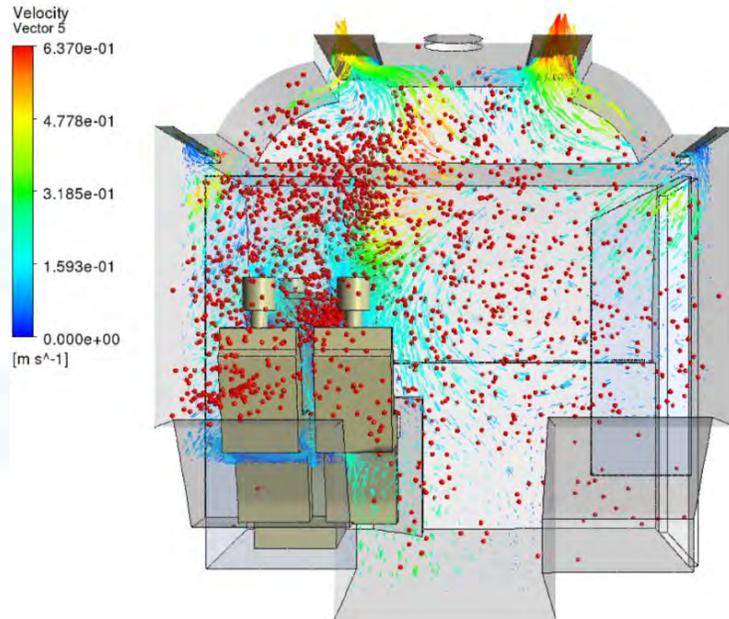
THE BUS CASE

Source position 1B



Aerosol distribution – 1B

Concentration at end of simulation (t=300s) for case with door openings



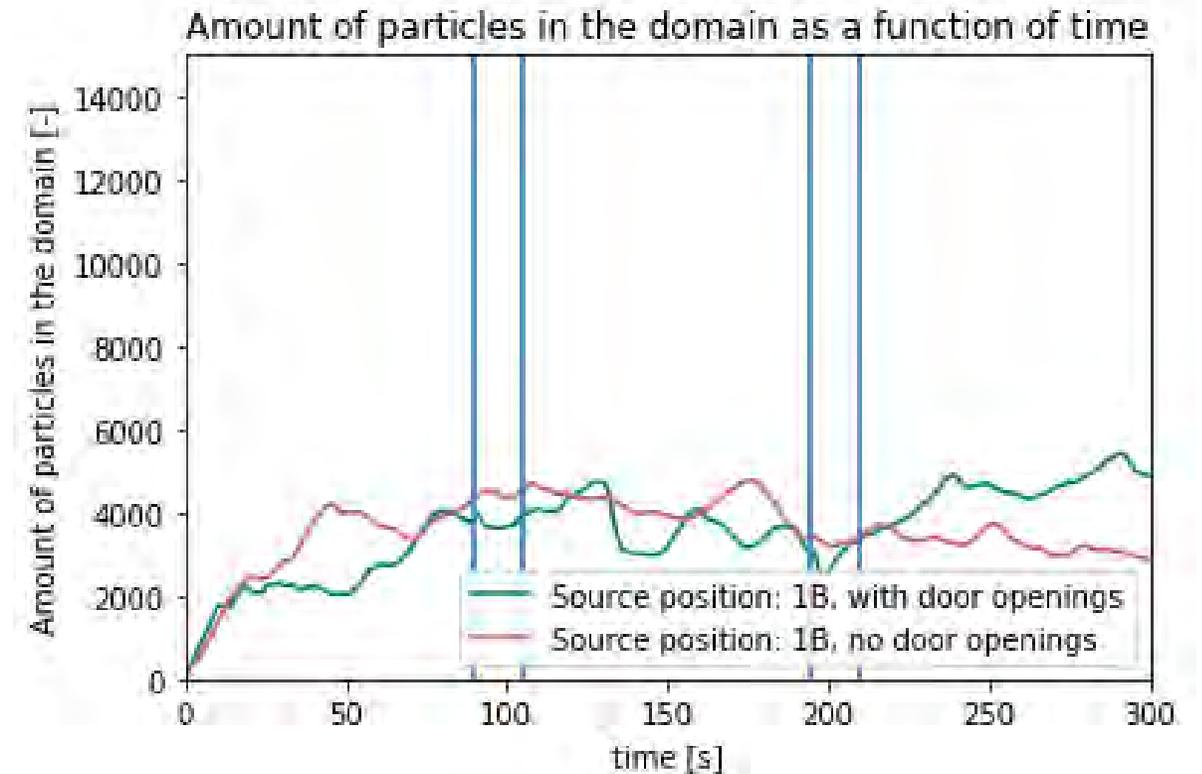
Particles are contained around the source since the source is located directly under the extraction vent. Majority of particles is extracted. A fraction of the particles reaches the recirculation bubble in the driver cabin.

Particle Faith Fractions [-]

Deposited	0.228
Extracted	0.678
Suspended	0.094

Aerosol concentration over time – 1B

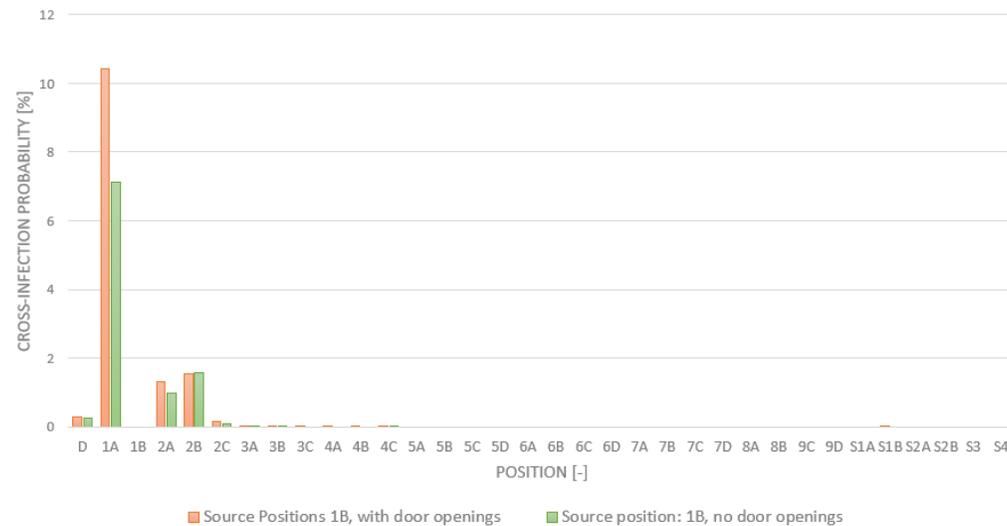
- Overall concentration is halved compared to a source positioned at 6A, since 1B is very close to the extraction vent.
- The proximity near the extraction vent also causes more fluctuations
- Overall concentration does not drop due to door openings



Cross-infection probability – 1B

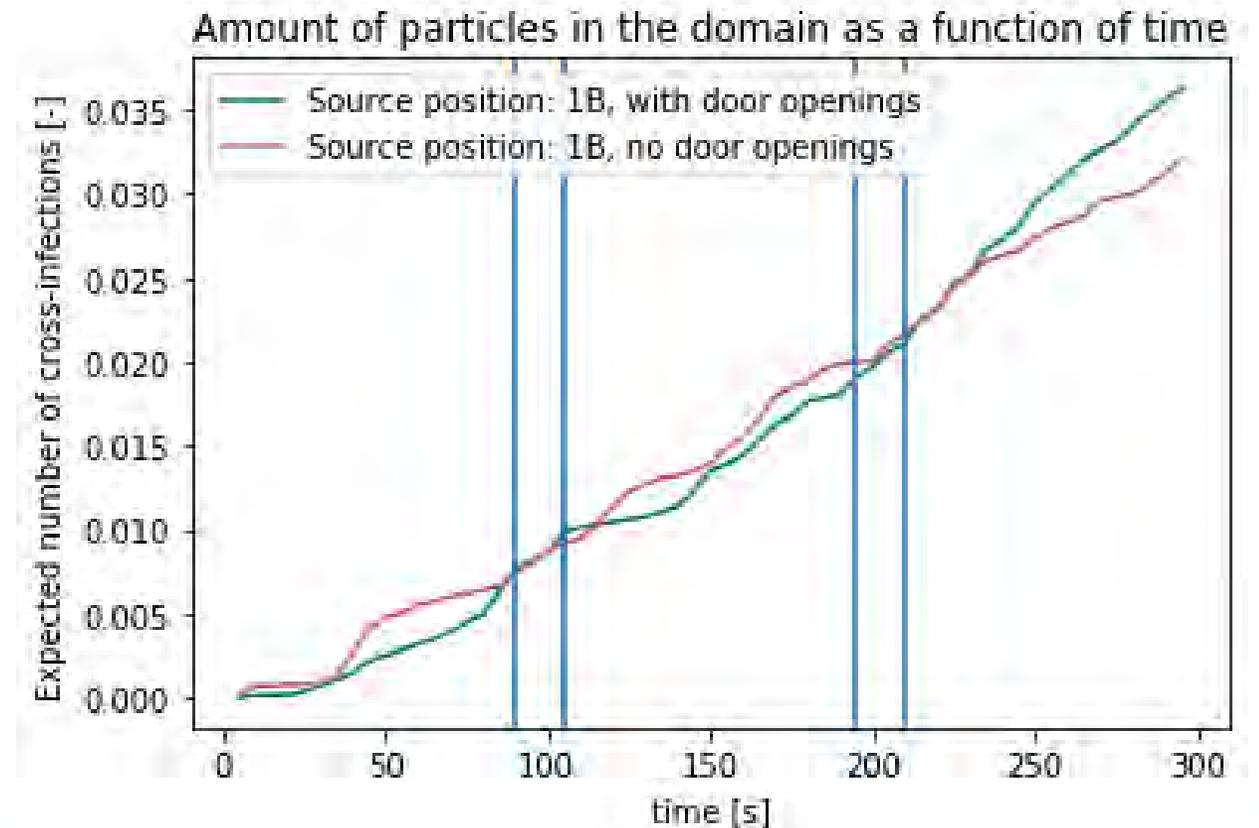
- Relatively high cross-infection risk for the adjacent passengers. Negligible cross-infection risk for other passengers
- Passenger closest to the driver but cross-infection risk for driver is still very low
- Increase cross-infection risk for the adjacent passenger due to the door opening

Individual cross-infection probability for a 15 minute journey



Effect of door openings on cross-infection risk – 1B

No clear impact of the door openings on the expected number of cross-infections

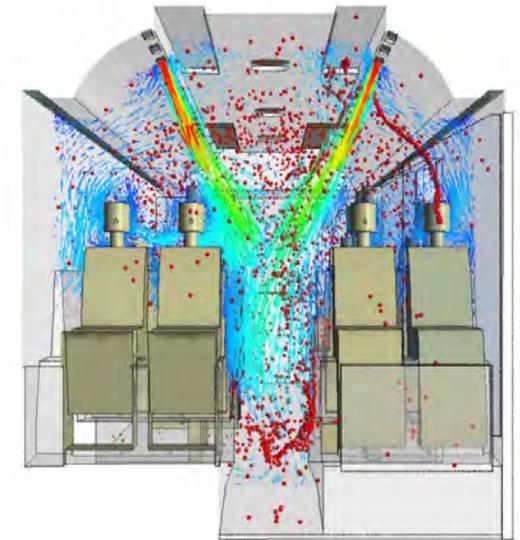
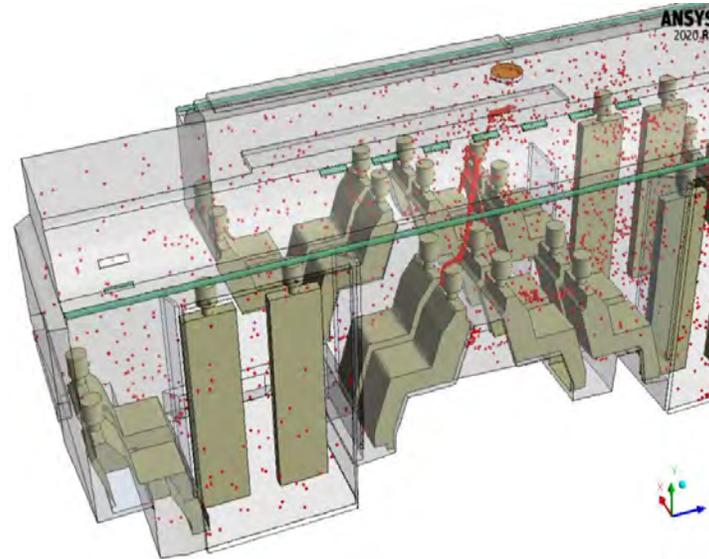


Aerosol distribution – 7D (facing backwards)

Concentration at end of simulation
with door openings (t=300s)

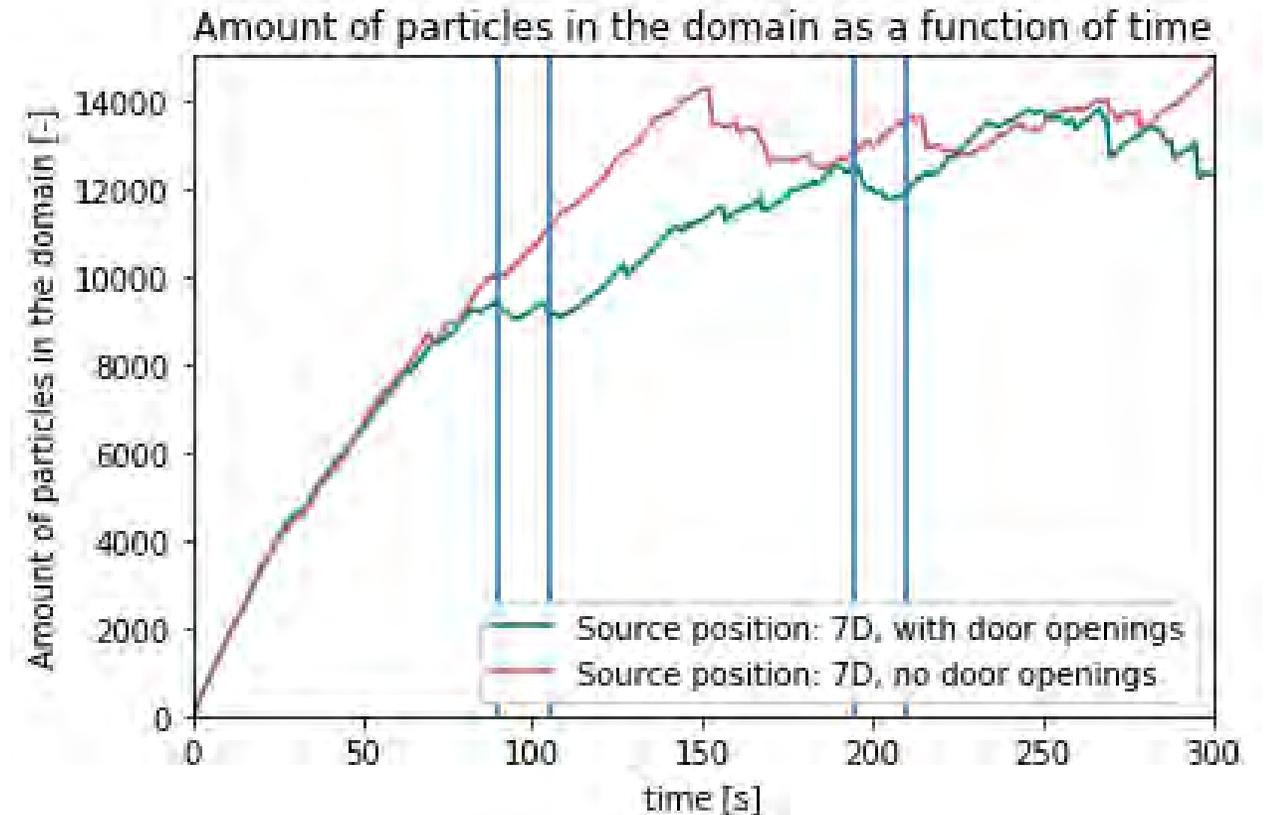
Particle Faith Fractions [-]

Deposited	0.561
Extracted	0.198
Suspended	0.241



Aerosol concentration over time – 7D

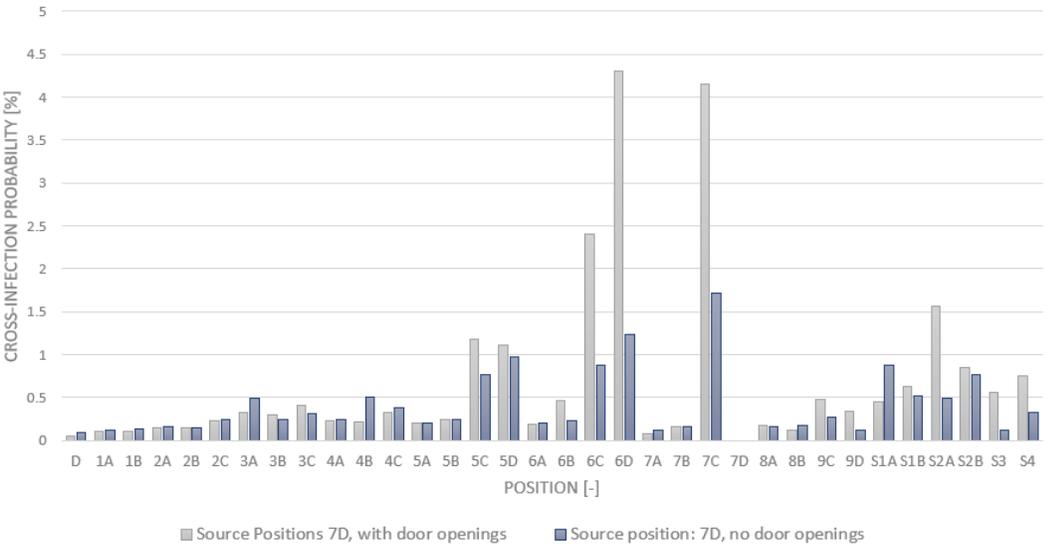
- High overall concentration of aerosols (14000 compared to 4000 for a source positioned at 1B)
- Door openings cause the overall concentration to plateau during the first door opening and decrease during the second door opening.
- Door openings causes the overall aerosol concentration to increase slower. However, a similar overall concentration is reached after a while



Cross-infection probability – 7D

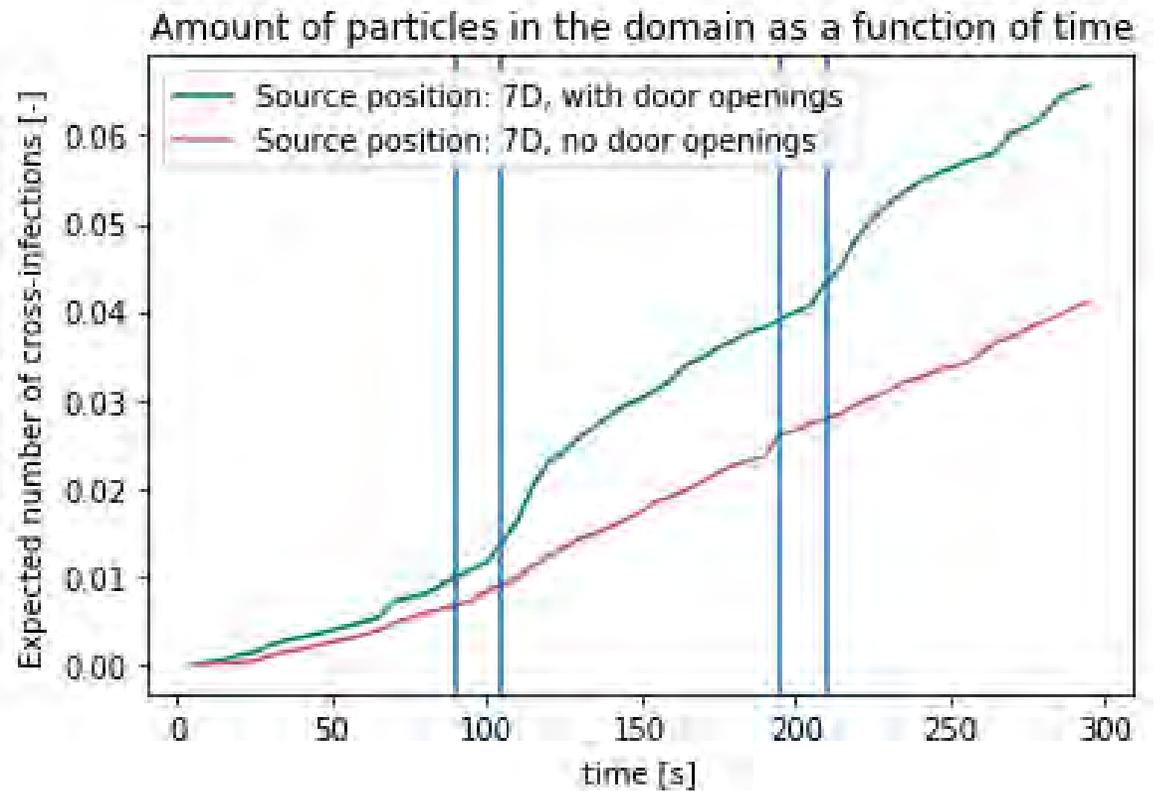
- Relatively high cross-infection risk for the adjacent passengers.
- Cross-infection risk is spread out over all passengers
- Notable increase in cross-infection risk in case the doors open

Individual cross-infection probability for a 15 minute journey



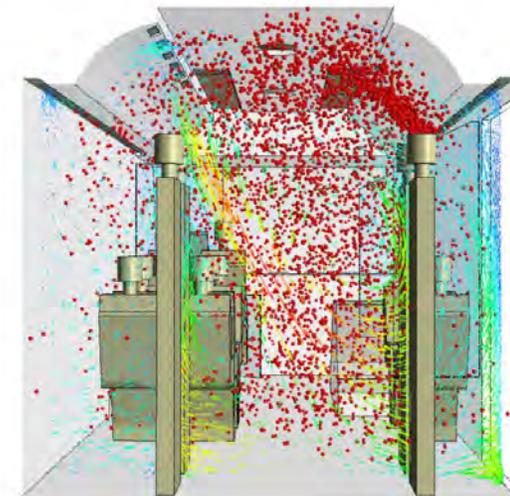
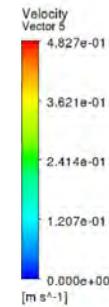
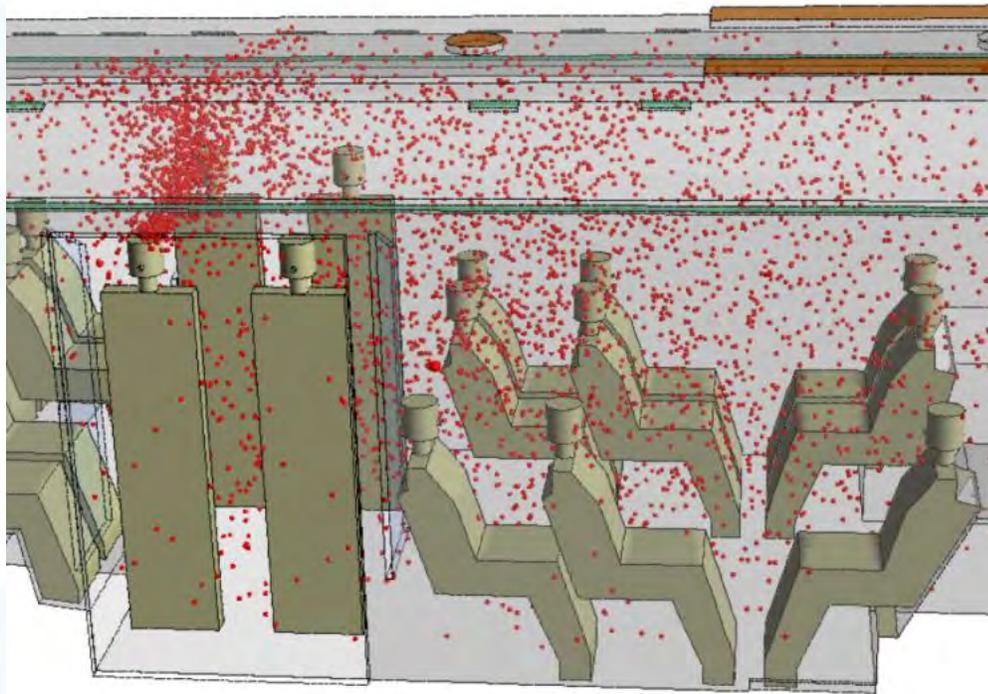
Effect of door openings on cross-infection risk – 7D

- Clear change in slope after the door openings causing a significant increase in expected number of cross-infections



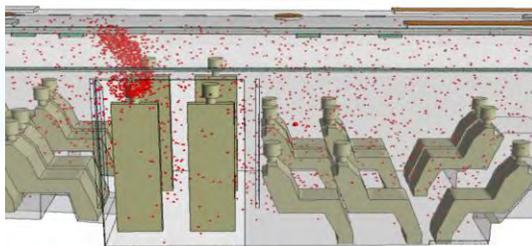
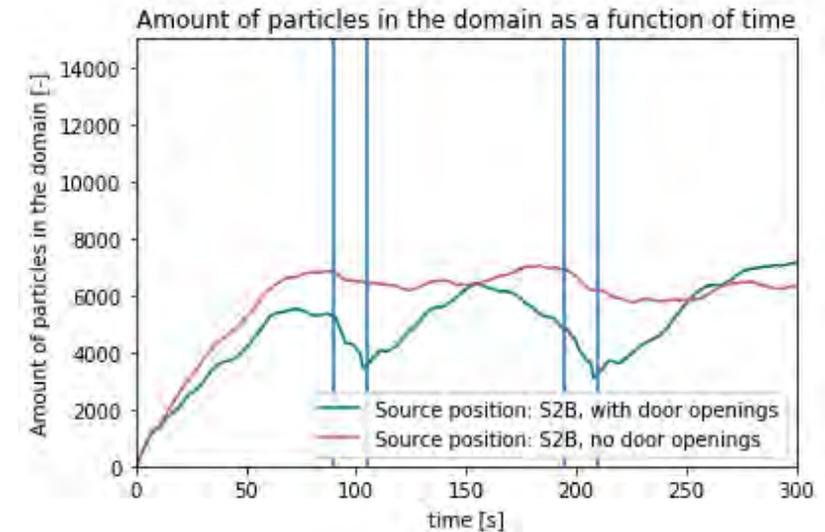
Aerosol distribution – S2b (standing)

Concentration at end of simulation (t=300s)

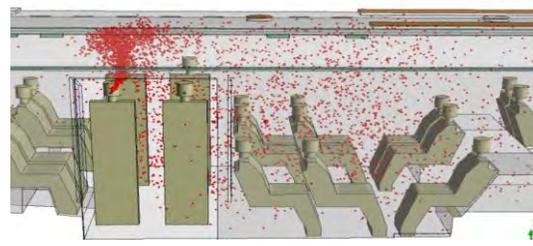


Aerosol concentration over time – S2b

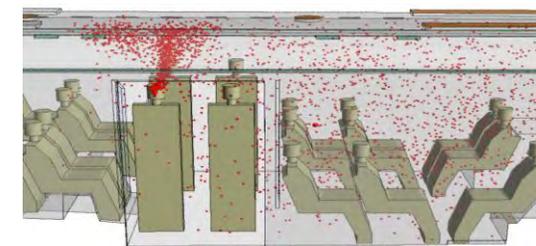
- Significant drop in aerosol concentration during the opening of the doors since source is just in front of the door
- Oscillation in-between door openings caused by cloud of aerosols which travels rearwards. After the door closes, the concentration increases while this cloud moves towards the extraction vent



t = 115s



t = 150s

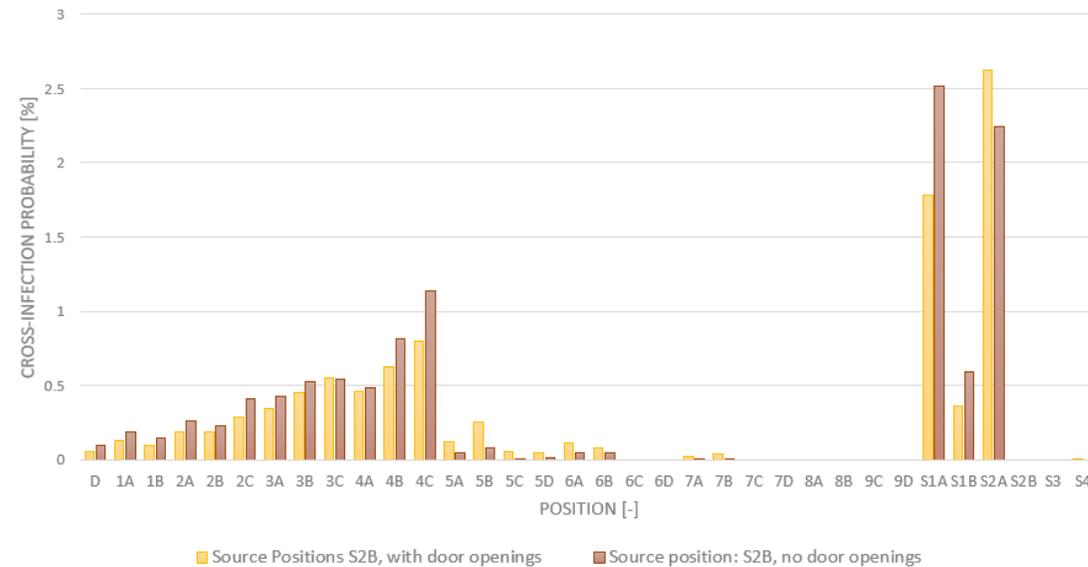


t = 195s

Cross-infection probability – S2b

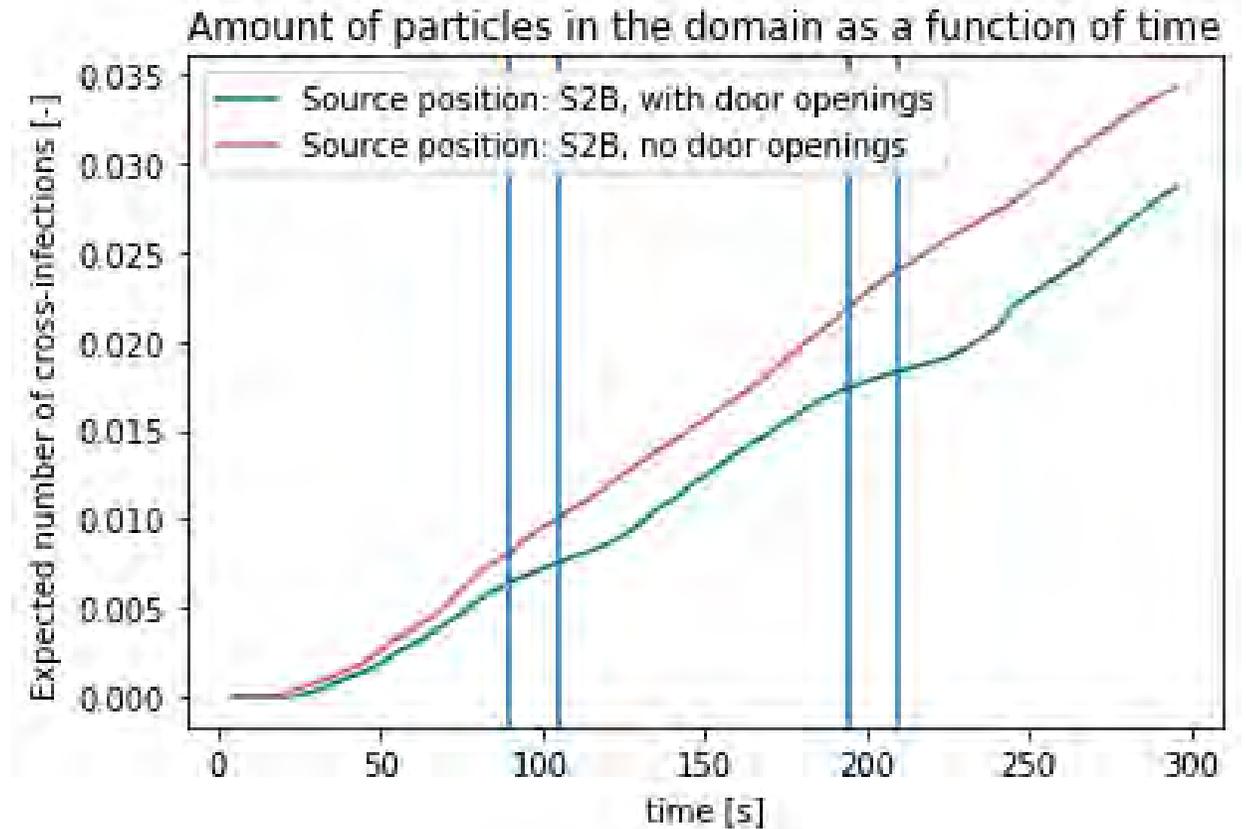
- Cross infection risk spread out over all passengers close and in front of the source
- Slight decrease in cross-infection risks for case with door openings but not conclusive

Individual cross-infection probability for a 15 minute journey



Effect of door openings on cross-infection risk – S2b

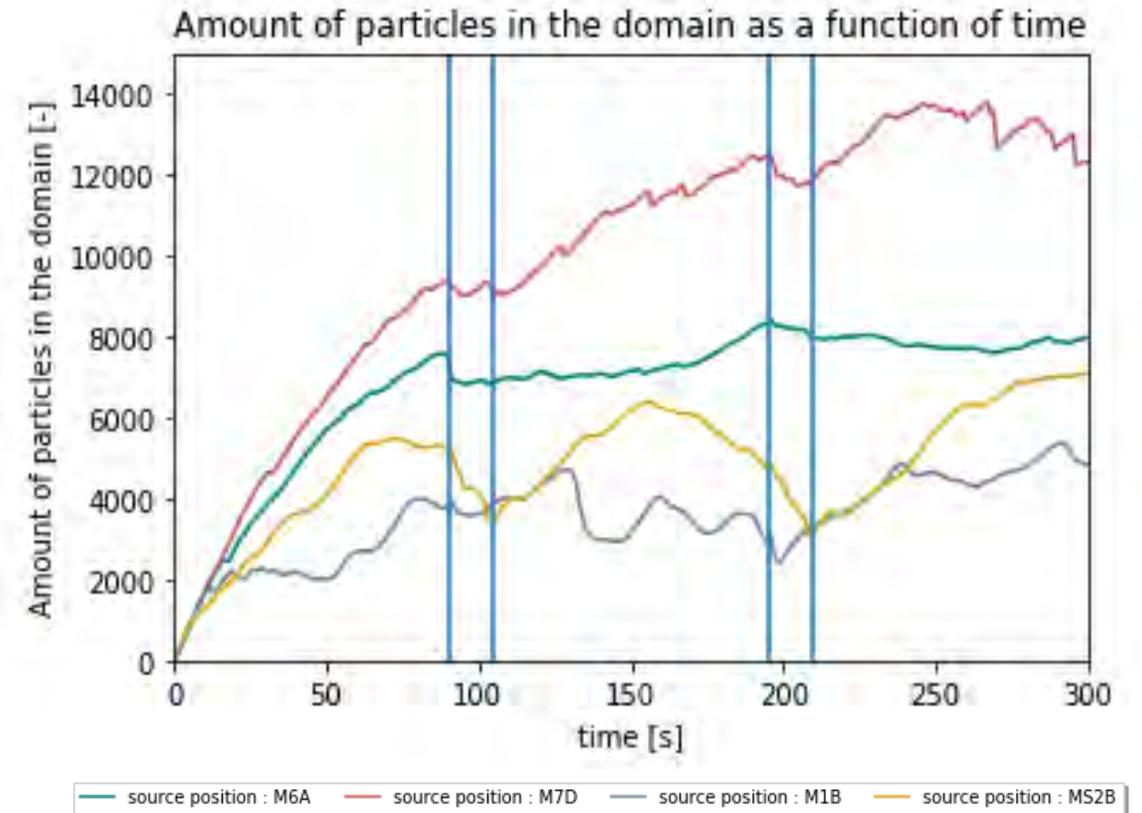
- Decrease in expected number of cross-infections for case with door openings



CONCLUSIONS for SOURCE POSITIONS

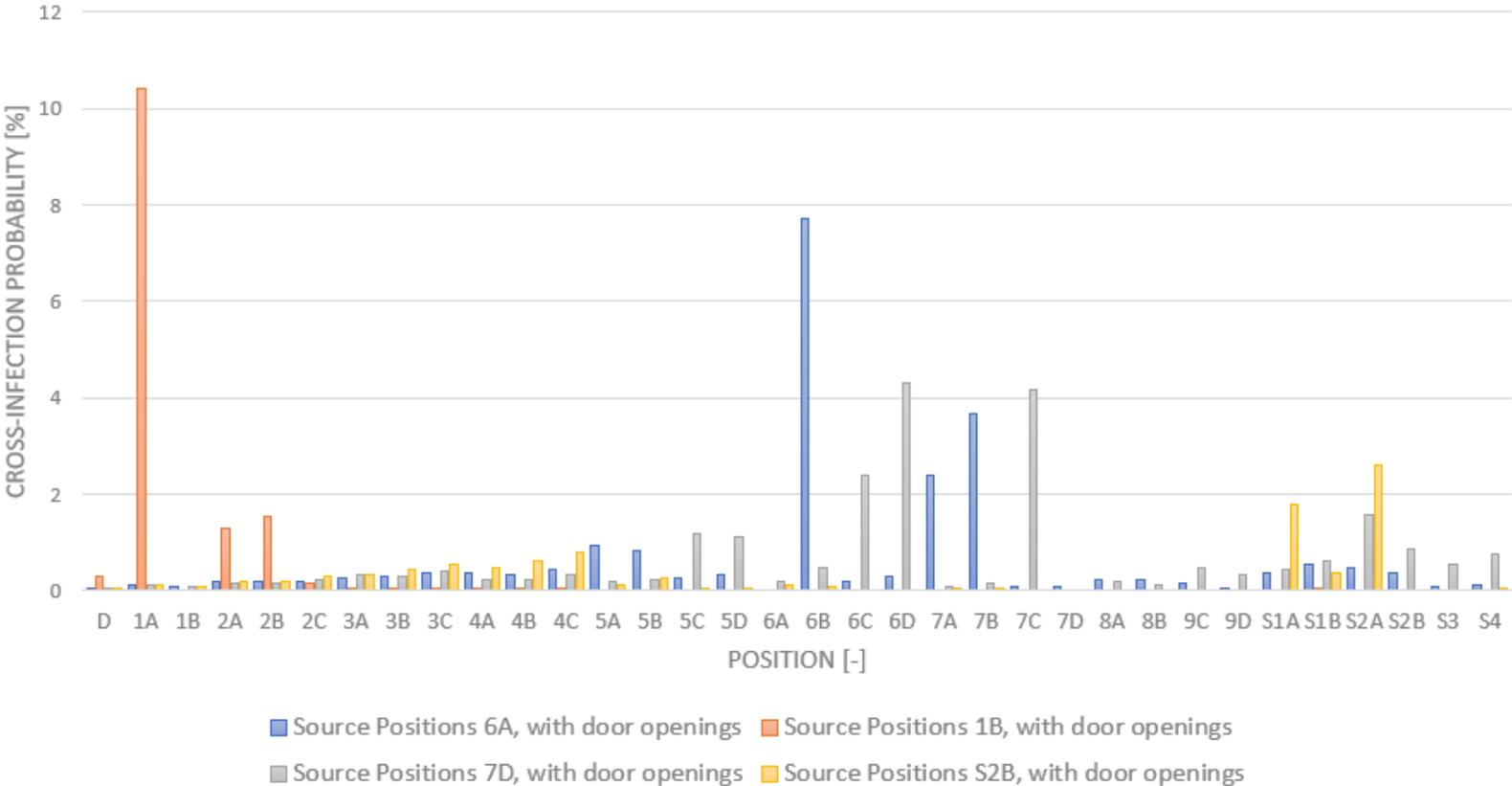
Comparison source positions for concentration of aerosols

- Overall concentration of aerosols the highest for source located at position 7D. Lowest for source at 1B



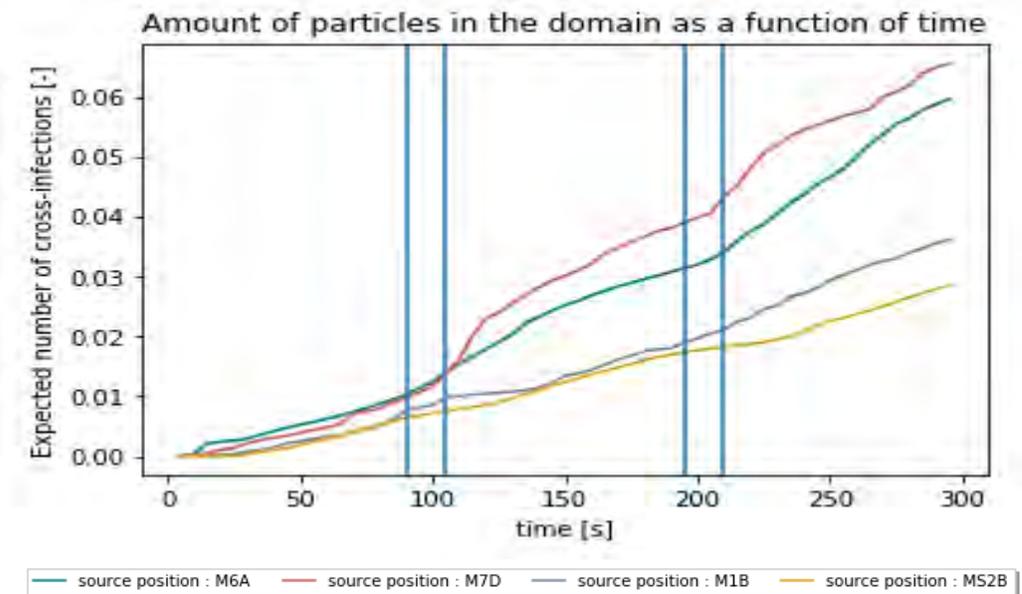
Comparison Source positions Individual cross-infection risk

Individual cross-infection probability for a 15 minute journey



Comparison Source Positions Expected number of cross-infections

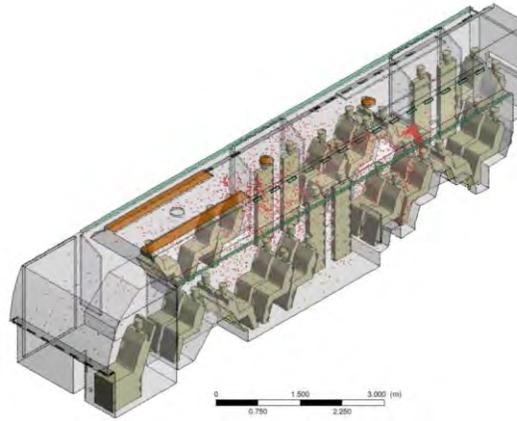
- Highest expected number of cross-infections if the source is seated nearer to the back of the bus
- Standing source leads to the lowest amount of expected number of cross-infections (likely due to door openings)



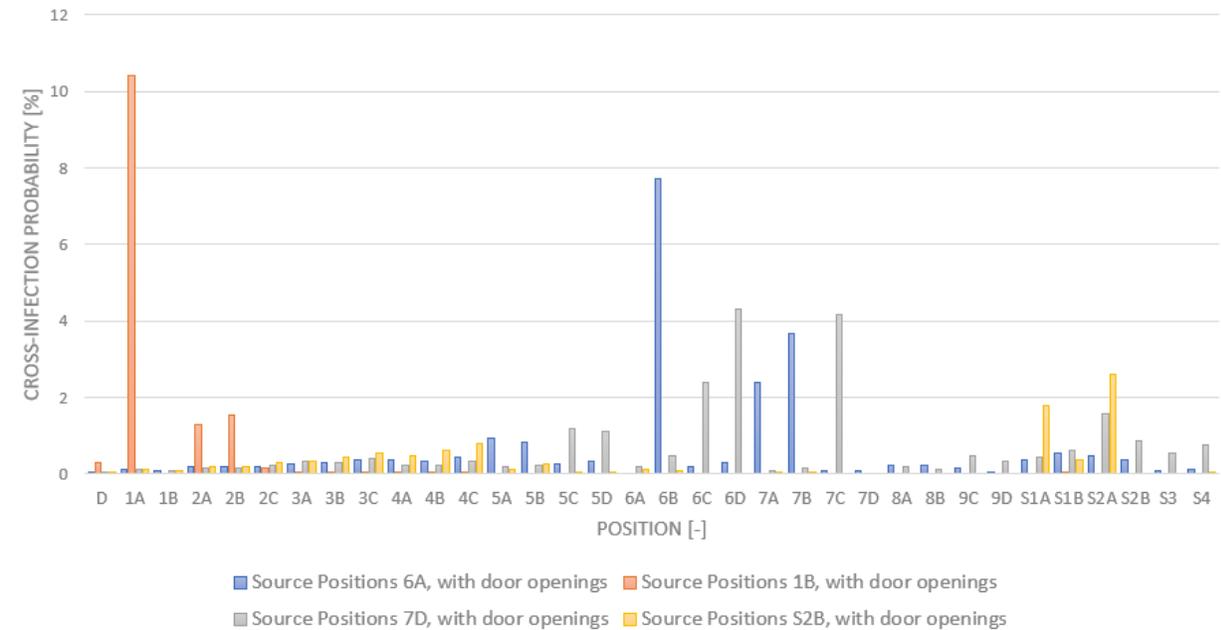
Conclusion and action points

Conclusion

- Calculated the distribution of aerosols in an urban bus with and without door openings for various source positions
- The resulting concentration field was used to estimate the cross-infection risk for a 15min journey
- The cross-infection risk of COVID-19 via inhalation of infected airborne droplets is relatively low due to the relative short duration of a typical journey on a city bus
- A social distance of 1.5m is not sufficient to prevent cross-infection
- The cross-infection risk is significantly reduced with the use of face masks
- In general, door openings do not result in a clear decrease in cross-infection risk



Individual cross-infection probability for a 15 minute journey



Action Points

Requested simulations for Bus:

- Recirculation outlet on the roof but in the back of the bus
 - No real added value, will mirror the current results
- Open roof hatches (with door openings)
 - Will be simulated next, will require some time/effort
- (Partially) sealing of the driver cabin
 - Completely sealing of the driver will lead to a 0 cross-infection risk. So why not fully seal off the driver. No real added value.
- Other ventilation rate, layout or re-circulation fraction
 - Potentially interesting
- Longer door openings
 - Not interesting

Requested simulations for Coach:

- Simulation with permanent supply vents
 - Will be performed

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Professor

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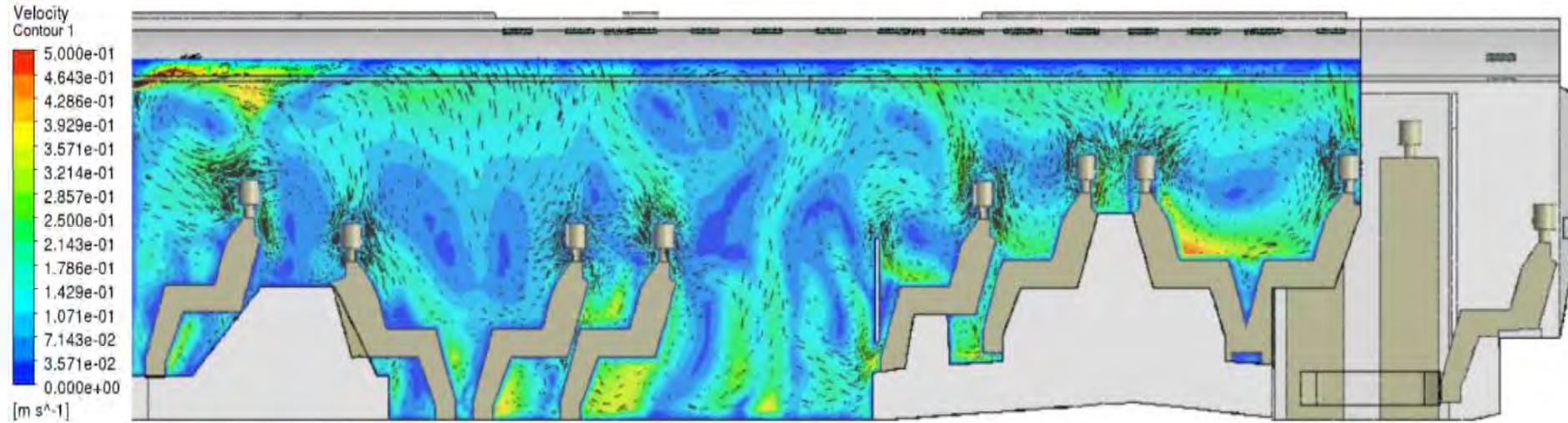
@ugent



Ghent University

Extra figures

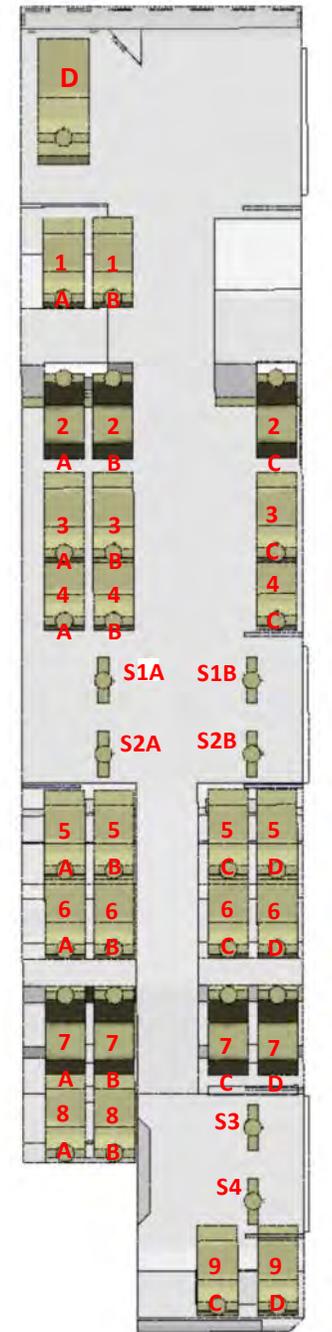
Passenger zone flow field



Passenger locations figure

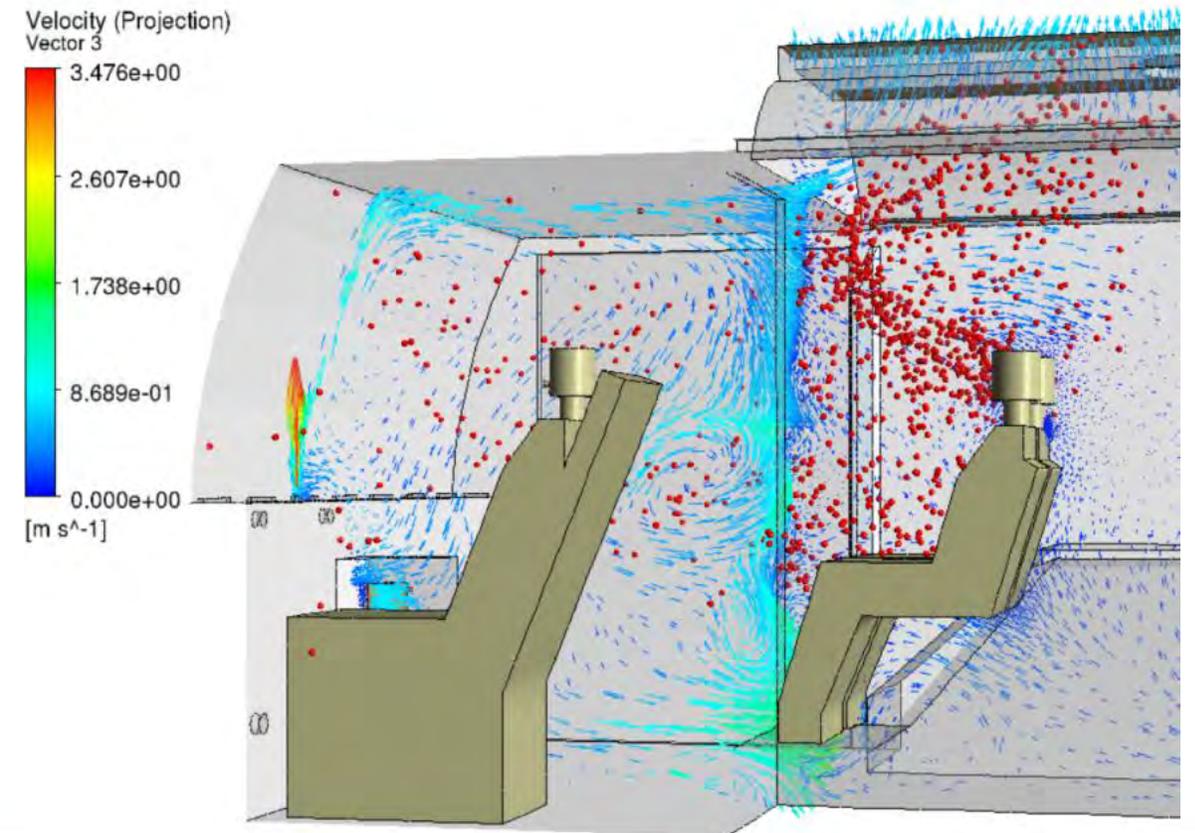
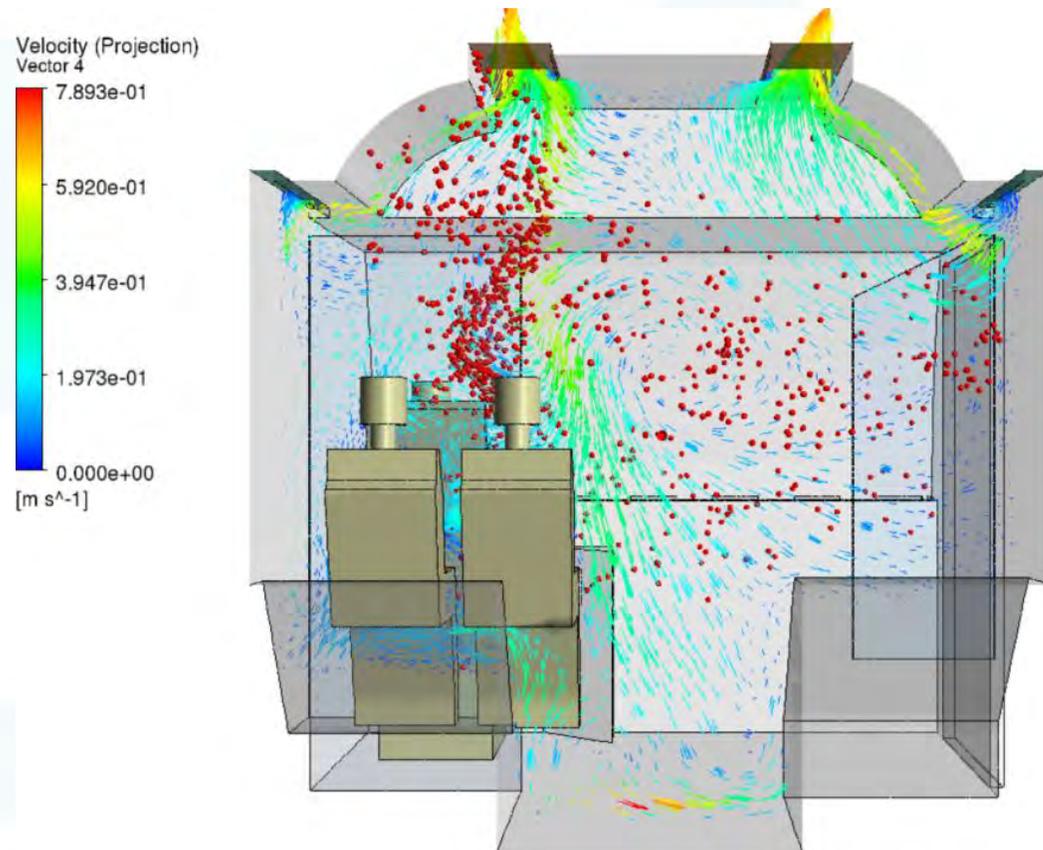


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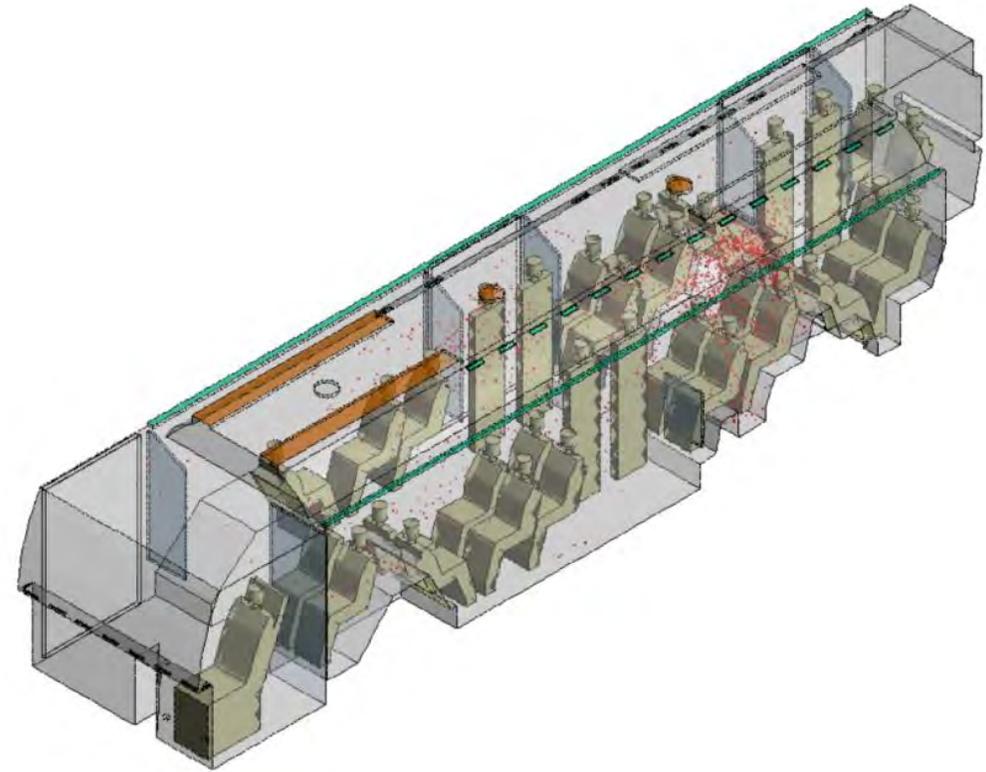
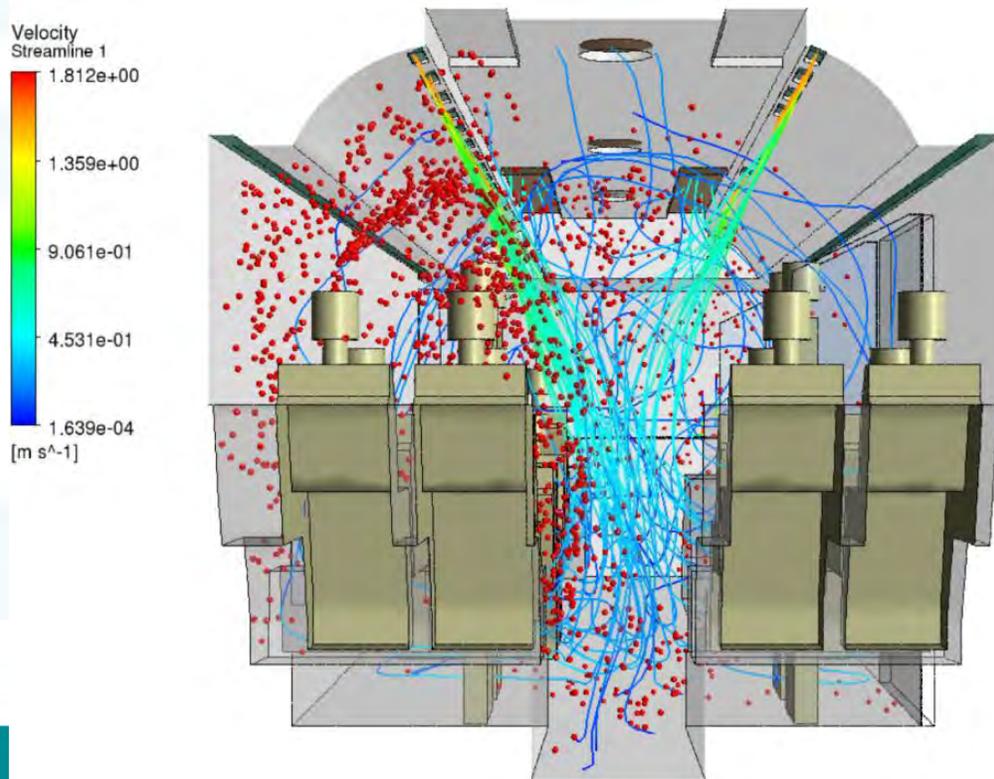


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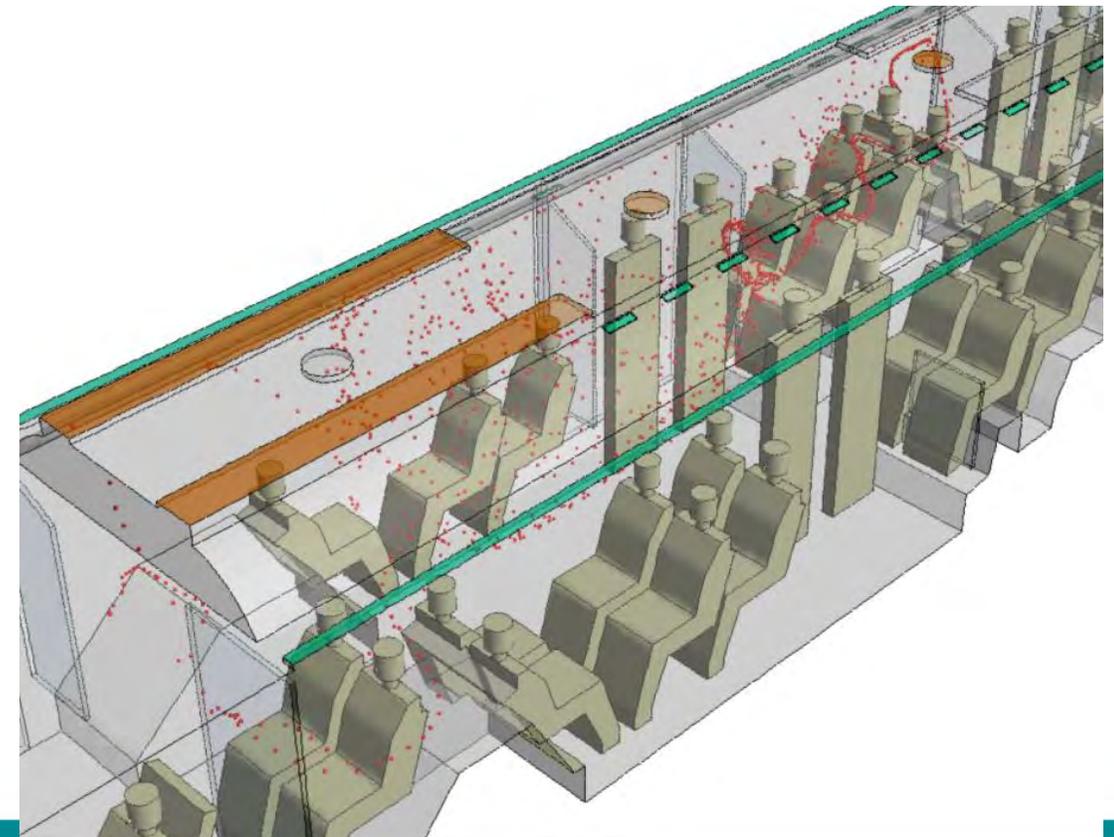
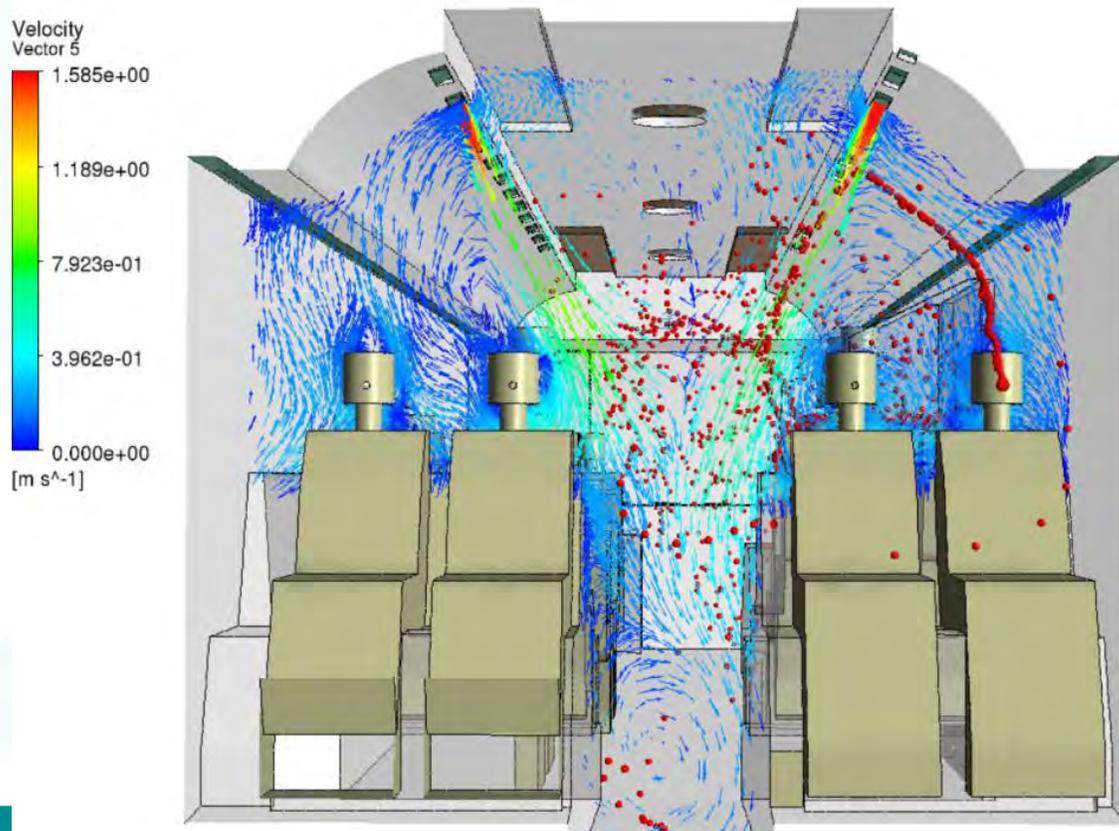
- Source at position C
- Aerosol distribution
- Supply vents in the driver cabin blow the aerosols away from the driver
- Particles are sucked upwards by the extraction vent
- 80.3% of particles are extracted, 19.7% is deposited



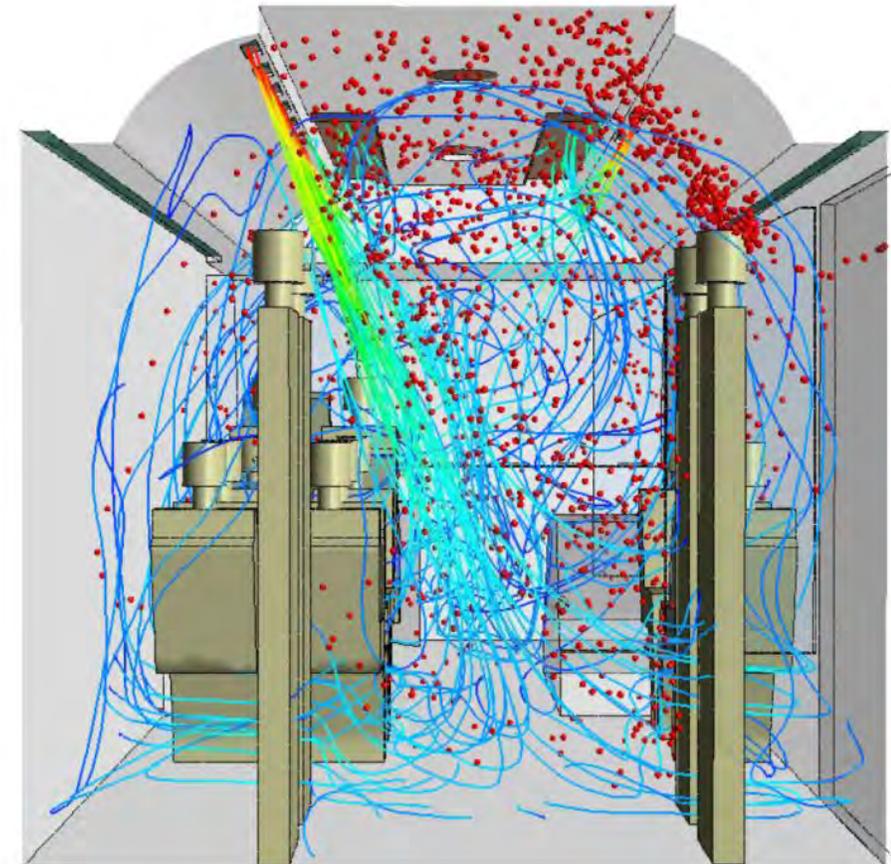
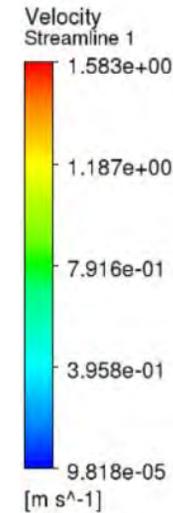
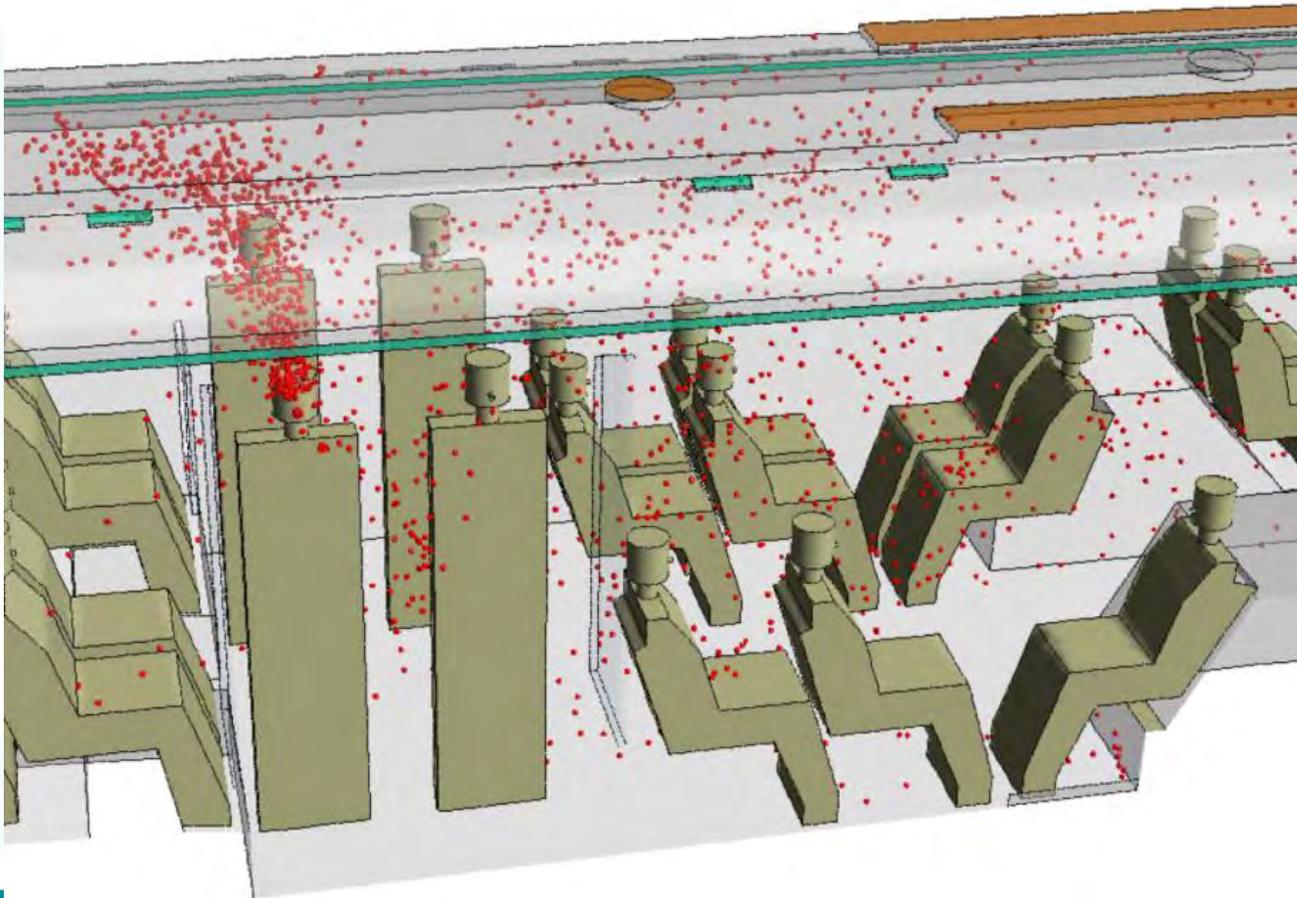
- Source at position 6A
- # Aerosol distribution
- Roof inlets create a swirling flow around the passengers
- Particles are forced upwards mainly by the dominant flow
- Aerosols spread towards front of the bus
- 21% of particles are extracted, 70% is deposited, 5% remains suspended



- Source at position D
- Aerosols following swirling flow towards the front of the bus
- 27.9% escapes the domain, 31.1% is deposited, 41% remains suspended

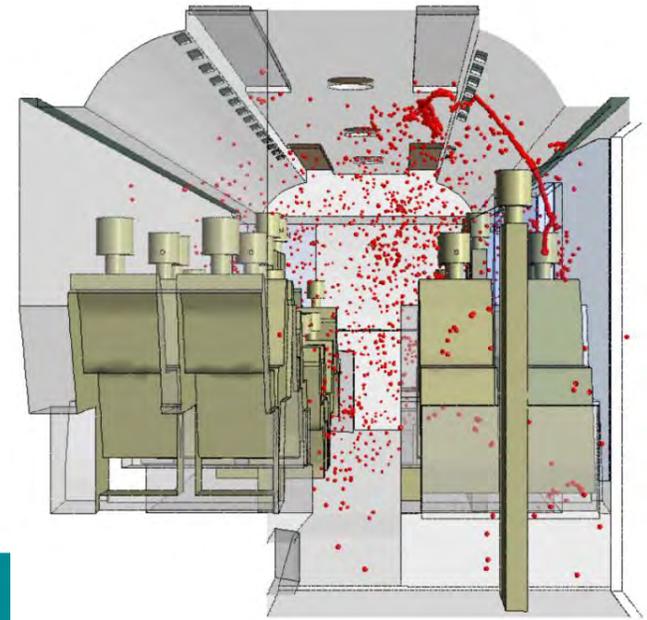
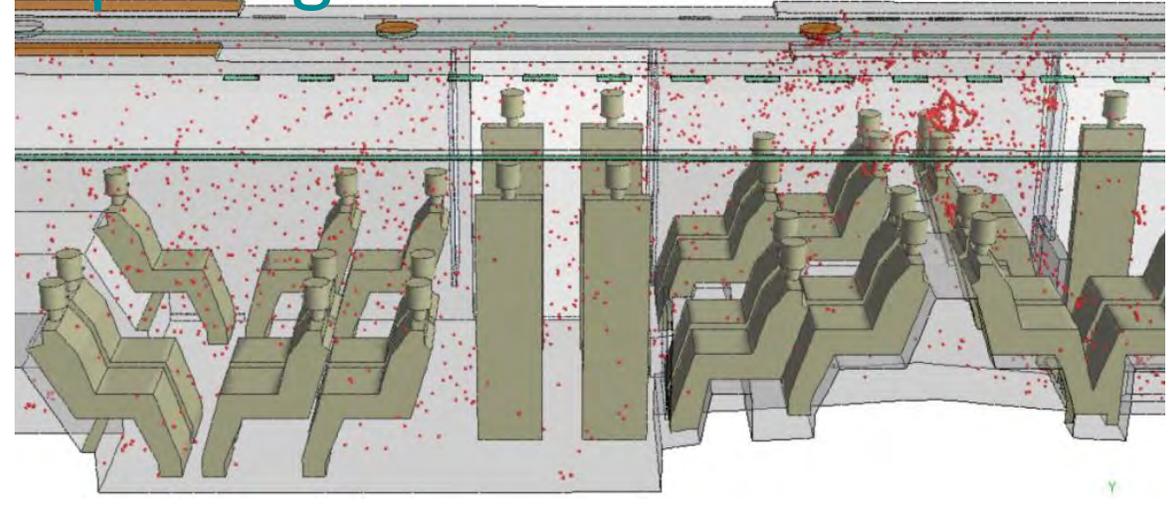
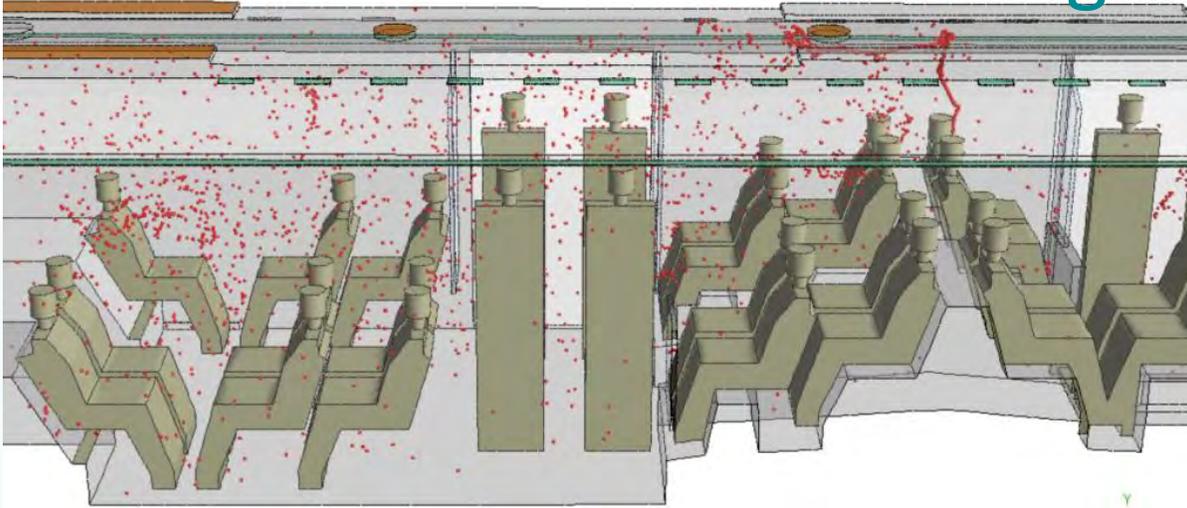


- Source at position §1B
- Accumulation of particles above the source patient's head
- Aerosols are sucked towards the extraction vent
- 31.6% escapes the domain, 68.4% is deposited



Just before door opening ($t=90s$) aerosol distribution during door opening

End of door opening ($t=105s$) aerosol distribution





BUSWORLD
foundation

the global bus alliance

AIR PURIFICATION

Objective

- To review the available air filtration system in the market
- To develop basic criteria to evaluate the best products available
- To evaluate the air filtration systems using basic criteria.

Criteria

- ✓ Effect on Viruses & bacteria
- ✓ Tested against Sars-cov2 (COVID-19)
- ✓ Use in the presence of people
- ✓ Toxicity
- ✓ Health hazards
- ✓ Operating cost or Energy consumption
- ✓ Performance
- ✓ Maintenance
- ✓ Disposables
- ✓ Speed of effectiveness
- ✓ Authorizes use for COVID- 19

Electronic anti-viral air purification techniques-review

- These Technologies adopt various methods to create Ionic reactions, Hydroxyl radicals, Reactive oxygen species, super oxide Anions and other free radicals that can react with contaminants.
 - The concepts and names may differ, but the operation mechanism for Electronic Air Purification systems are majorly the same.
-
- Photocatalysis
 - Photocatalytic Activation
 - Ionization
 - Bi-Polar Ionization
 - Needle Point Ionization
 - Plasma
 - Hydro Peroxide Plasma
 - Activated Oxygen surface Irradiation
 - High Voltage Coronas
 - Hydroxylation
 - Cold Catalyst filter
 - Ionic Purifier-Composite Catalyst combo
 - NCCO (Nano Confined Catalytic oxidation)
 - Activated Oxygen surface Irradiation
 - UV Sanitizer – Negative Ions Combo

Technics being evaluated

1. Ionisation
2. Ozone based
3. UV-light based
4. Photocatalysis
5. Hypochlorous acid
6. HEPA filters

1. Ionization based air filtration system for buses/coaches

Operation Principle

Ionizer creates positive and Negative Ions

The Ions are distributed in the coach

The Ions surrounds the Pathogens

Without the Bonds the viruses are denatured

Bonds are severed in the Viral Envelope



Available Ionization Concepts

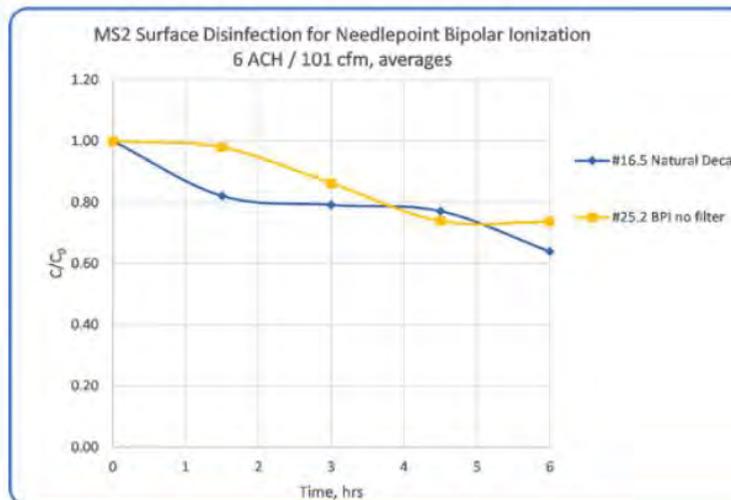
1. Needle Point Bi-Polar Ionization
2. Plasma Ionization
3. High Voltage Corona
4. Negative Ionization

Most Manufacturers claim;

Systems can reduce particulate matter count by agglomeration

Surface Inactivation of COV-2 > 99%

Removal of VOC's + Formaledehyde



EVALUATION

- There is not much of a difference, from Natural Viral decay on Surfaces and Surface Ionization reduction. (manufacturers claim is negligible)
- Ozone is created from Ionization sparks and in long periods significant amounts can be produced.
- Incomplete oxidations may occur and release harmful Byproducts Formaldehyde and Volatile Organic Compounds(VOC's)

2. ECO3 Ozone based air filtration system for buses/coaches (“VOLVO Concept”)

- **Principle:**

- ✓ An Ozone generator in the climate system continuously procedures active oxygen.
- ✓ These active oxygen can be transported through filters, airduct and a suitable number “ hundreds "of air outlets in the coaches.
- ✓ It is very active to combat viruses and bacteria which are in the air and all interior surfaces such as floors, seats, handles and glass panels. Also, it can reach every hard to access corners where only air can reach.
- ✓ Effective disinfection using negative ions and ozone (< 0.05 ppm); eco3, which operates by generating negative ions and ozone in recommended proportions, increases the oxygen concentration in the air, eliminates bad odors and maintains the air supply at healthy levels so that it doesn't become stale and polluted.
- ✓ eco3 is located in the suction and filtering system of the air conditioning unit and starts working automatically as soon as the air conditioning (AC, heating, ventilation) goes on.

- **Test results**

Proven effective in all vehicles
Cultures were taken from vehicles fitted with, and without the eco3 air purifier. Laboratory tests showed (where the eco3 was fitted) colony-forming units of bacteria's (CFU/m³) were reduced by 93% and plate-forming units of virus (PFU/m³) were reduced by 99.7%.



Effects of OZONE ???

<10% reaches the extraxction vents

5. Hypochlorous Acid as in Bailey Zero Hazard Solution

How do Dis-Infectants work on Viruses?

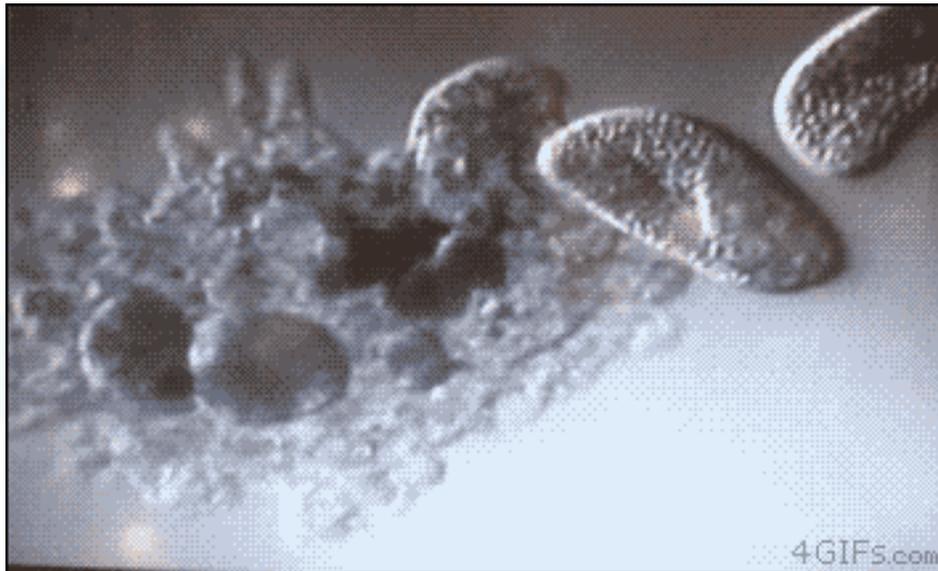
On contact with viruses, a disinfectant agent changes the protective protein envelope of the Virus, which loses its structure and aggregates.

Hypochlorous acid is naturally produced by Human white Blood cells and is an essential part of the Human Immune system. Phagocytosis is one of the most harmless reactions in the Human physiology, whereby Hypochlorous acid eliminates Pathogens.

It has been Inferred that Hypochlorous acid is an effective Biocide without the disadvantages of Biocides.

- The product works by coating the surface using fogging in a more effective way.
- Wiping of the surface is not required due to small size of the droplets.
- The usage and treatment time depends on the area and configuration of materials.
- It kills 99.9% of viruses & bacteria.
- It also works for emerging viral pathogens including covid 19 virus

Anti-Viral efficiency Phagocytosis- (Inside Humans)



On contact with viruses, a disinfectant agent changes the protective protein envelope of the Virus, which loses its structure and aggregates.

The animation above shows on a molecular level the destruction of pathogens in a Human by Hypochlorous acid-Phagocytosis Microscopic view.

6. HEPA FILTERS

Particulate Filtration can be very efficient at Filtering the Covid-19 Virus

According to research by *Benedette Cuffari*; the airborne particulates which contain the COVID-19 Virus, are about 0.5 - 0.9 Microns.

When the virus is in the air, It is part of the respiratory particulates and droplets expelled from Infected individuals.

We can Infer that HEPA filters can trap these particulates that spread the Virus, making HEPA filters efficient in Trapping the Virus as long as its in the air.

Problem : <10% reach the extraction vent

