Case studies

What is the particle dynamics in classrooms?

Indoor vs. outdoor exposure

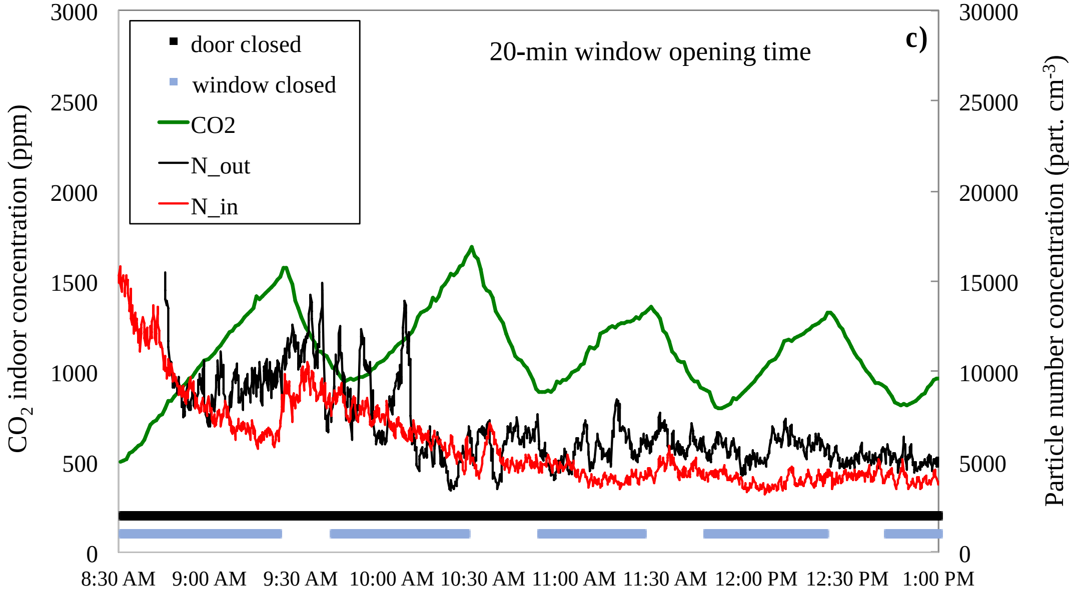
Exposure at schools: emission vs. ventilation

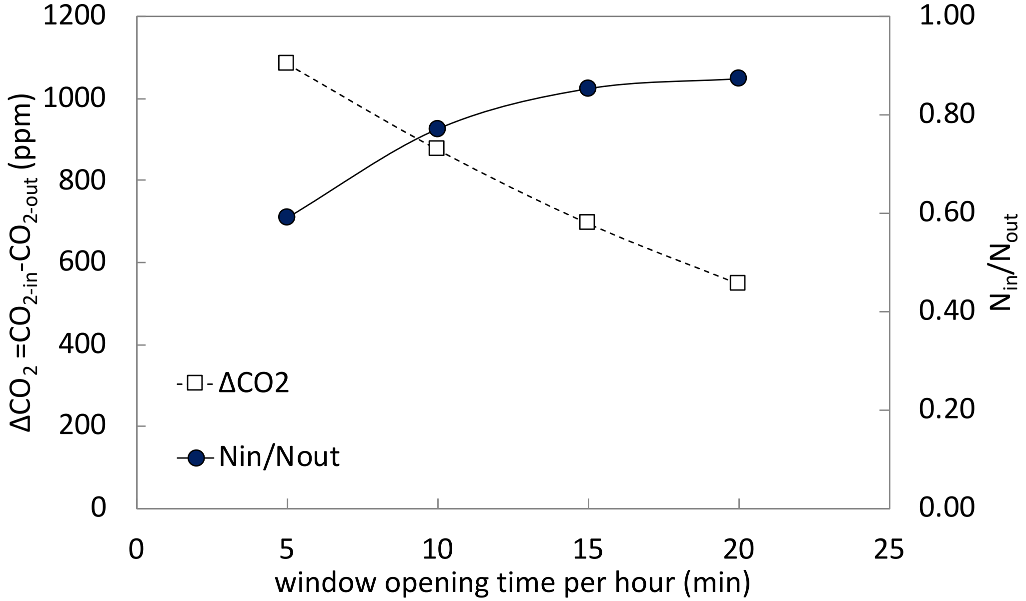
- Measurements of PM_{10}, Number concentrations, CO_2
- Naturally-ventilated classrooms (pre-retrofit)

Diffusion Charger Particle Counter

DustTrak photometer 8534: PM_{10}

Non-dispersive infrared analyzer: CO_2, T & RH



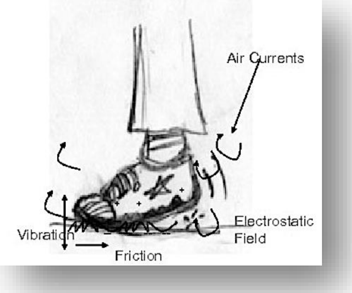


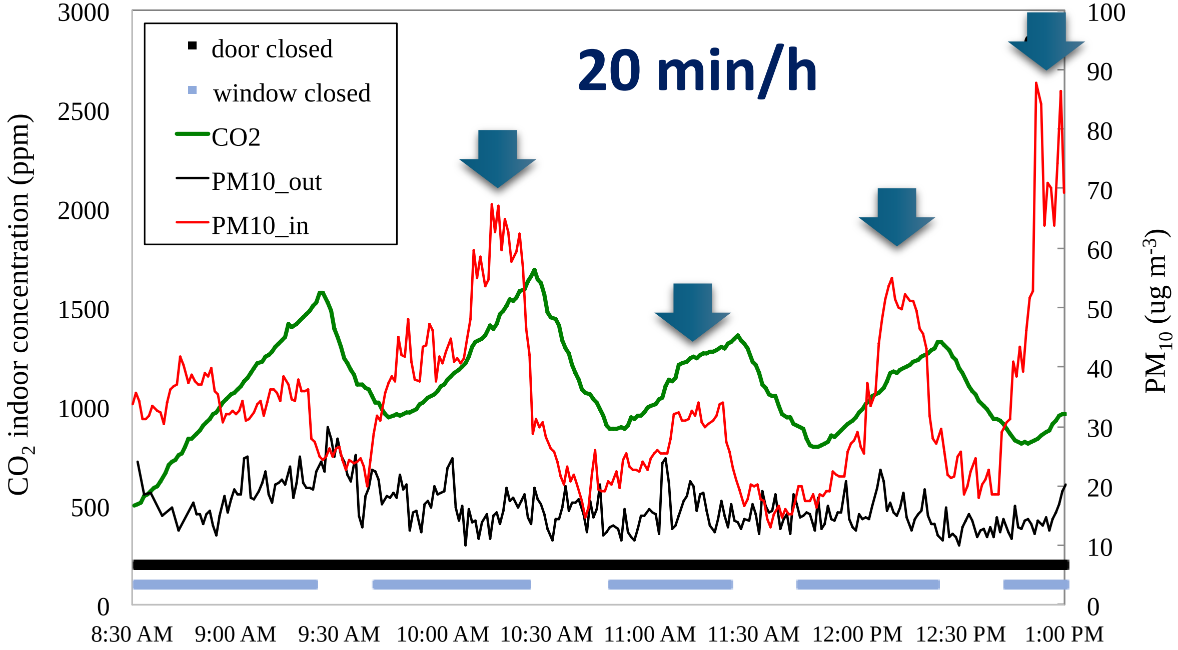
Stabile, L., Buonanno, G., Frattolillo, A., Dell'Isola, M., 2019. The effect of the ventilation retrofit in a school on CO 2 , airborne particles, and energy consumptions. Building and Environment, 156, 1-11, DOI: 10.1016/j.buildenv.2019.04.001

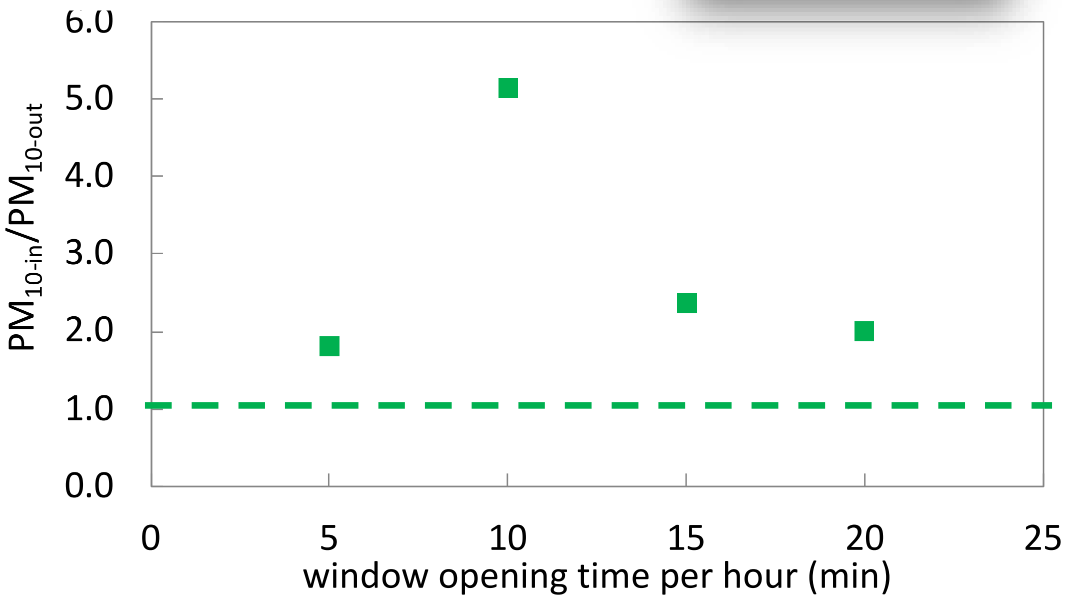
Indoor vs. outdoor exposure

Exposure in schools: emission vs. ventilation

- Measurements of PM_{10}, Number concentrations, CO_2
- Naturally-ventilated classrooms (post-retrofit)





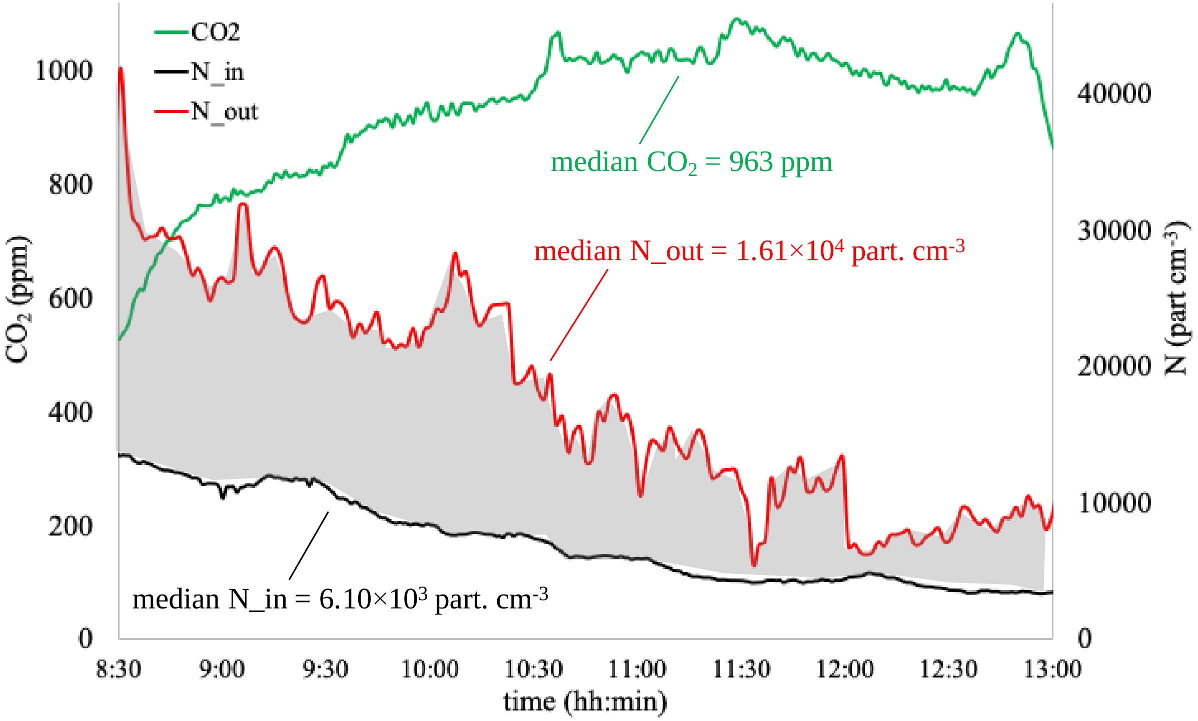


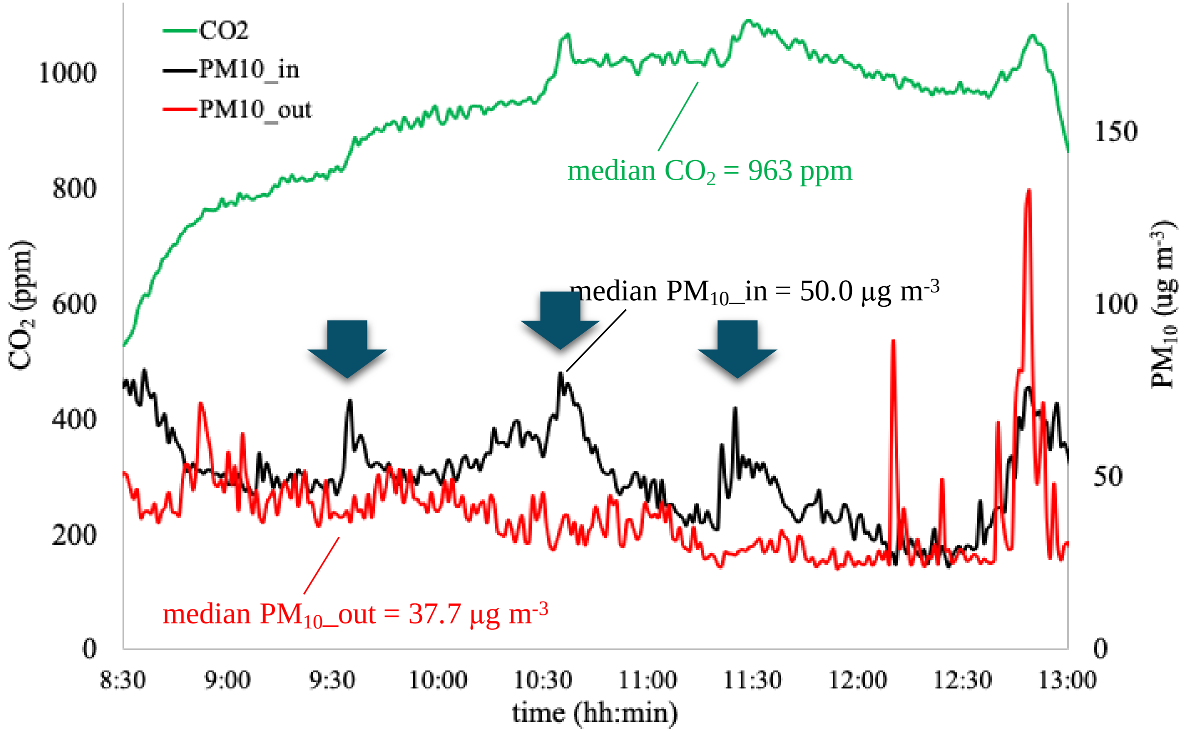
Manual airing reduces CO_2 (and indoor-generated gaseous pollutants) but increases sub-micrometric particles (effect on PM_{10} negligible)

Indoor vs. outdoor exposure

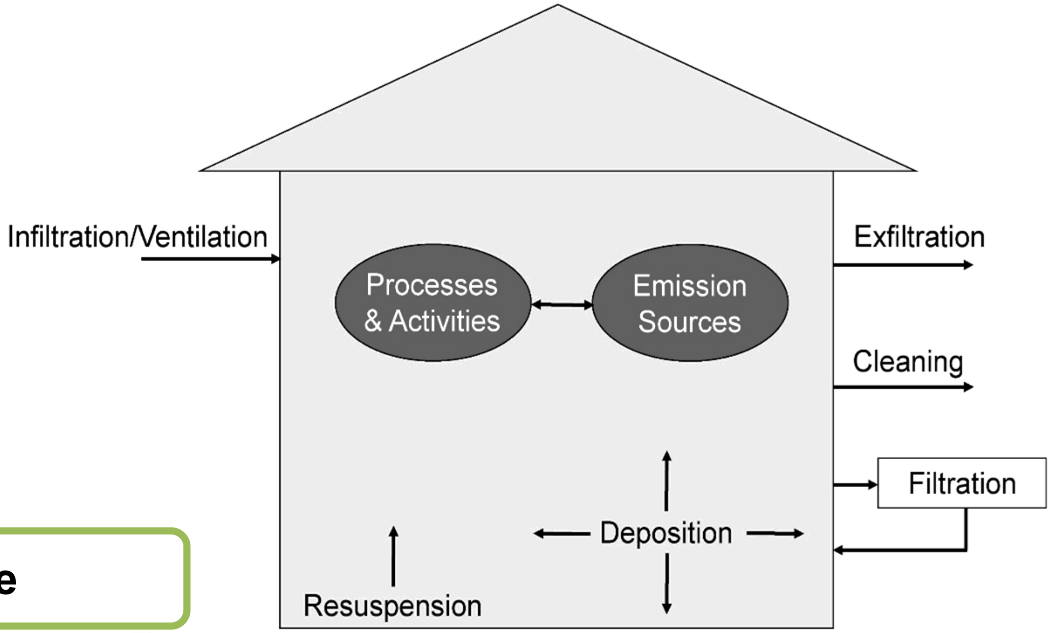
Exposure in schools: emission vs. ventilation

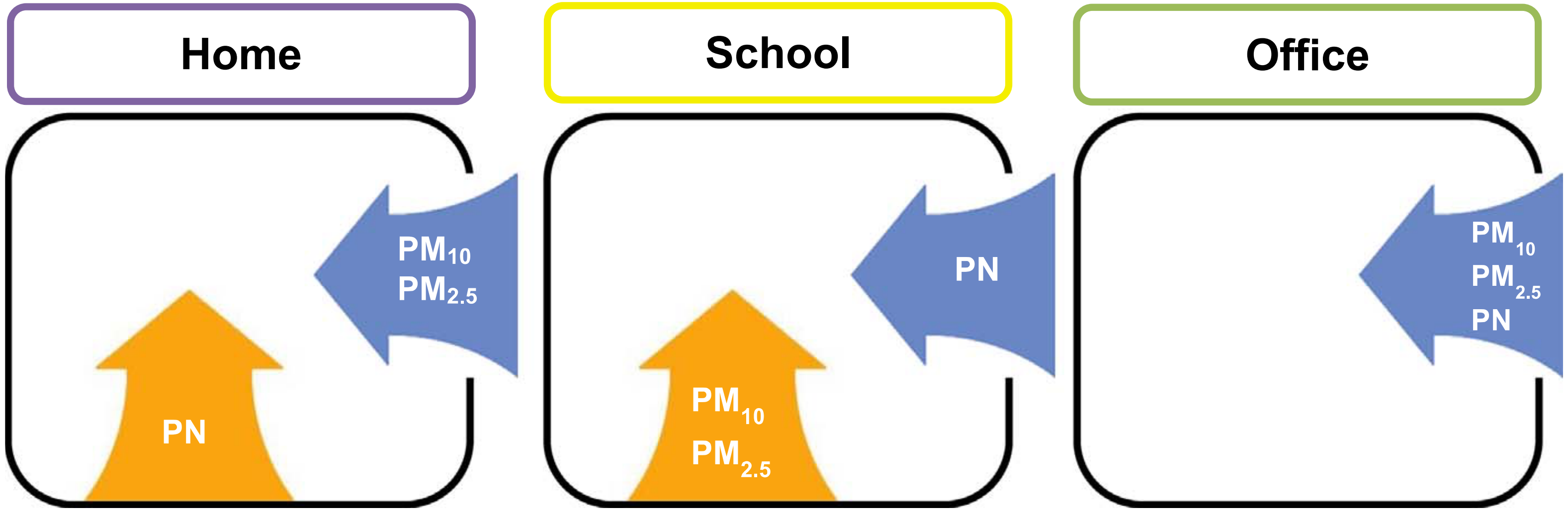
- Measurements of PM_{10}, Number concentrations, CO_2
- Mechanical ventilated classrooms (post-retrofit)





Indoor vs. outdoor exposure





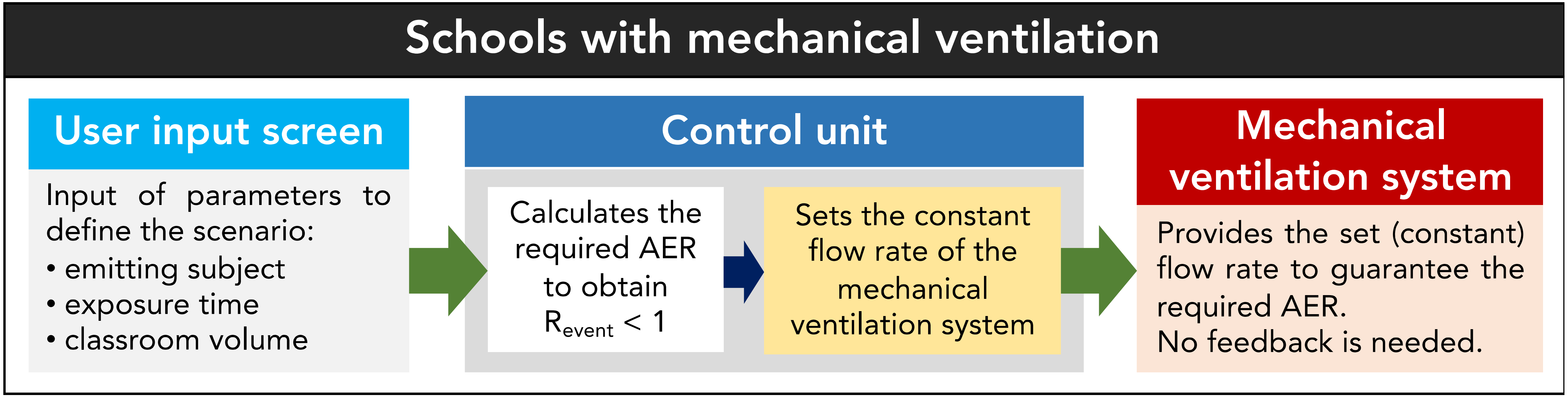
Morawska, L., Afshari, A., Bae, G. N., Buonanno, G., Chao, C., Hänninen, O., Hofmann, W., Isaxon, C., Jayaratne, R., Salthammer, T., Waring, M., Wierzbicka, A., 2013, Indoor Aerosols: From Personal Exposure to Risk Assessment, Indoor Air, 23 (6), 462-487

Manual airing to reduce airborne transmission?

Methodology: scenarios

Scenarios		Emitting subject	Emission duration (min), respiratory activity	Description
Base scenarios	T-60-LS	teacher	60 min, loudly speaking	Infected teacher giving lesson for the first 60 min of the school-day loudly speaking
	S-0%-S	student	300 min, oral breathing	Infected student attending lessons for five hours (100% of the school-day) oral breathing
Student's speaking effect	S-10%-S	student	30 min, speaking & 270 min, oral breathing	Infected student attending lessons for 270 minutes (90% of the school-day) oral breathing and speaking for the rest of the time (10%)
	S-20%-S	student	60 min, speaking & 240 min, oral breathing	Infected student attending lessons for 240 minutes (80% of the school-day) oral breathing and speaking for the rest of the time (20%)
	S-30%-S	student	90 min, speaking & 210 min, oral breathing	Infected student attending lessons for 210 minutes (70% of the school-day) oral breathing and speaking for the rest of the time (30%)
	S-40%-S	student	120 min, speaking & 180 min, oral breathing	Infected student attending lessons for 180 minutes (60% of the school-day) oral breathing and speaking for the rest of the time (40%)
Voice modulation effect	T-60-S	teacher	60 min, speaking	Infected teacher giving lesson for the first 60 min of the school-day speaking (e.g. using a microphone)
Mask effect	T-60-LS-M	teacher	60 min, loudly speaking	Infected teacher giving lesson for the first 60 min of the school-day loudly speaking. Students and teacher wear surgical masks.
Voice modulation & mask mask effect	T-60-S-M	teacher	60 min, speaking	Infected teacher giving lesson for the first 60 min of the school-day speaking (e.g. using a microphone). Students and teacher wear a surgical mask.

Stabile, L., Pacitto, A., Mikszewski, A., Morawska, L., Buonanno, G., 2021. Ventilation procedures to minimize the airborne transmission of viruses in classrooms. Building and Environment, 202, 108042, DOI: 10.1016/j.buildenv.2021.108042



Schools with mechanical ventilation

User input screen

Input of parameters to define the scenario:

- emitting subject
- exposure time
- classroom volume

Control unit

Calculates the required AER to obtain $R_{event} < 1$

Sets the constant flow rate of the mechanical ventilation system

Mechanical ventilation system

Provides the set (constant) flow rate to guarantee the required AER.
No feedback is needed.

Morawska et al., Making indoor air quality standards in public buildings the reality: moving forward. *Science*, in press

1. We considered a classroom, assuming that susceptible individuals remained in the microenvironment for the same amount of time (1 hour) as the infected individual (SARS-CoV-2 Delta variant).

2. The scenario consisted of a 150 m^3 classroom (total area of 50 m^2 , populated with 25 students + 1 teacher with 2 m^2 /student) in which a seated infected student emitted infectious particles through 80% oral respiration and 20% phonation, while the exposed susceptible students were seated (not wearing personal protective equipment).

3. No exceptional events such as coughing or sneezing were considered in the evaluation of the infectious particle emission rate of the infected person.

4. In addition, ventilation of 14 $L\ s^{-1}$ $person^{-1}$ (corresponding to approximately 9 ACH) was assumed.

5. Once all boundary conditions were defined for a prospective assessment of the long-range airborne transmission, we used the AIRC tool to estimate the individual probability of infection and to verify whether the event reproduction number (Re) was maintained below 1.

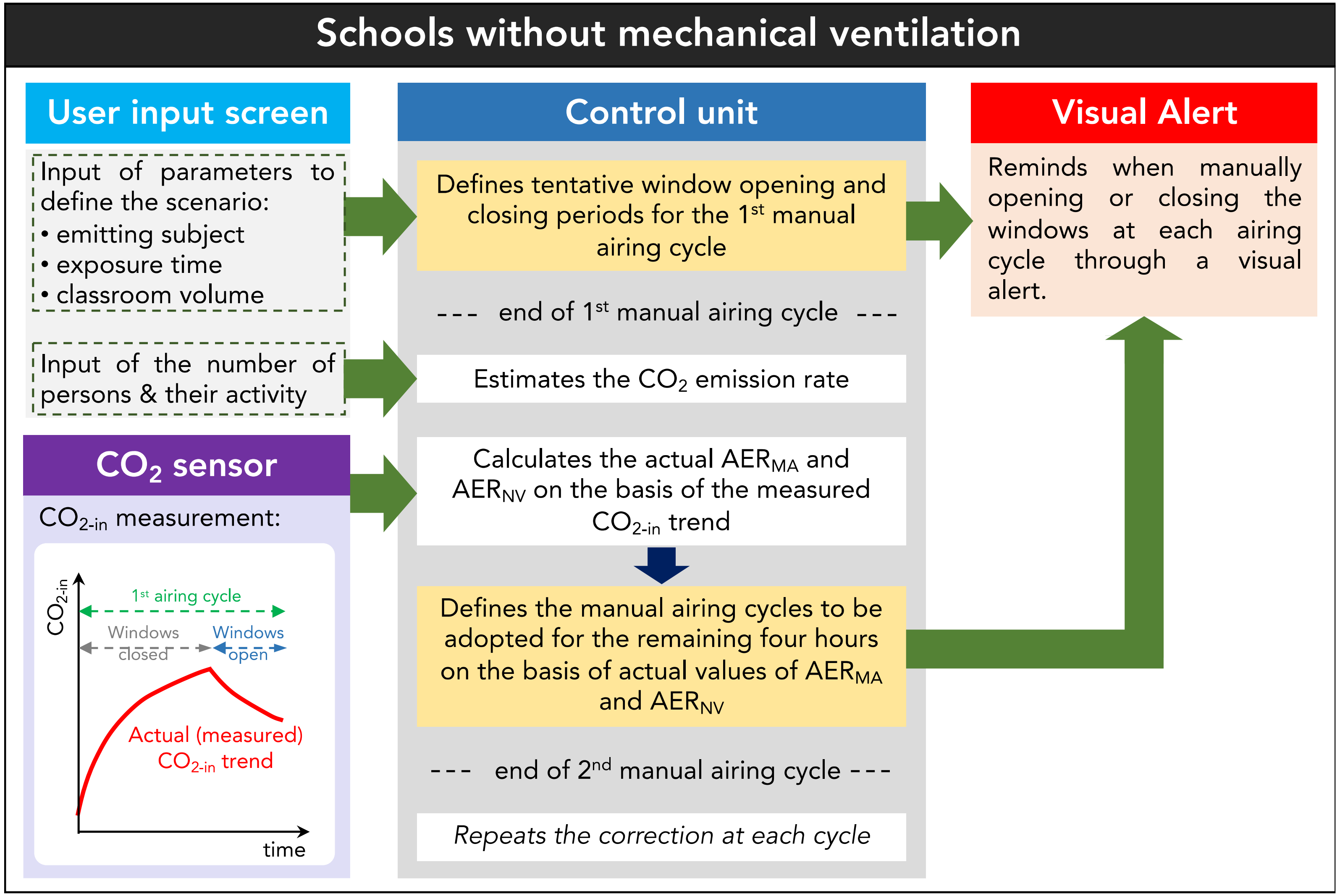
6. The infection risk was 2.9%, confirming that with a gathering of 25 students, the condition Re<1 was met (Re continued to stay below 1 until the maximum speaking value of 40%).

7. A CO_2 value in the steady-state condition lower than 800 ppm was obtained, with a background CO_2 of 450 ppm.

8. Consequently, a CO_2 threshold value for this scenario could be 800 ppm (350 ppm as an increase over the outdoor value).

Morawska et al., Making indoor air quality standards in public buildings the reality: moving forward. *Science*, in press

Results: procedures



Schools without mechanical ventilation

User input screen

Input of parameters to define the scenario:

- emitting subject
- exposure time
- classroom volume

Input of the number of persons & their activity

CO_2 sensor

$CO_{2\text{-in}}$ measurement:

Control unit

Defines tentative window opening and closing periods for the 1st manual airing cycle

--- end of 1st manual airing cycle ---

Estimates the CO_2 emission rate

Calculates the actual AER_{MA} and AER_{NV} on the basis of the measured $CO_{2\text{-in}}$ trend

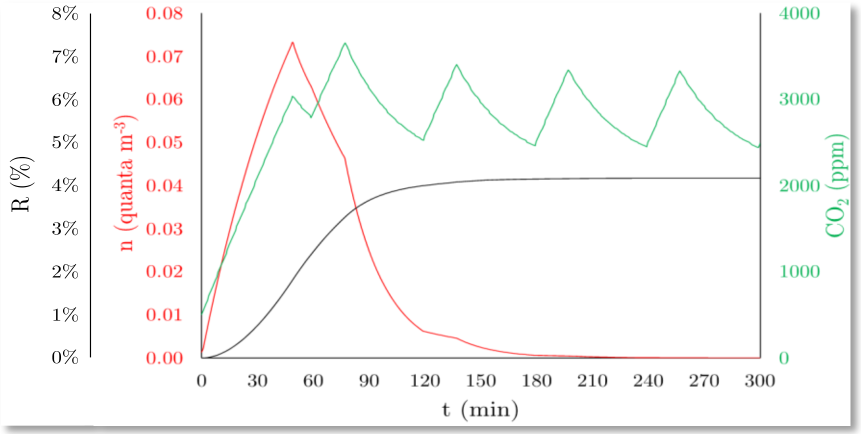
Defines the manual airing cycles to be adopted for the remaining four hours on the basis of actual values of AER_{MA} and AER_{NV}

--- end of 2nd manual airing cycle ---

Repeats the correction at each cycle

Visual Alert

Reminds when manually opening or closing the windows at each airing cycle through a visual alert.



Mechanical ventilation?


Airdog
10
SODECA

The government of the central Italy's Marche region on March 2021 launched a 9 M€ call to fund the installation of MVSs in classrooms to prevent the airborne transmission of SARS-CoV-2 and limit the adoption of distance learning solutions.

There were a total of 10 441 classrooms with an average occupancy of 20 students per classroom. 10 125 classrooms relied on natural ventilation (i.e. ventilation due to the leakages of the building and to the manual opening of the windows) while 316 were equipped with MVSs.

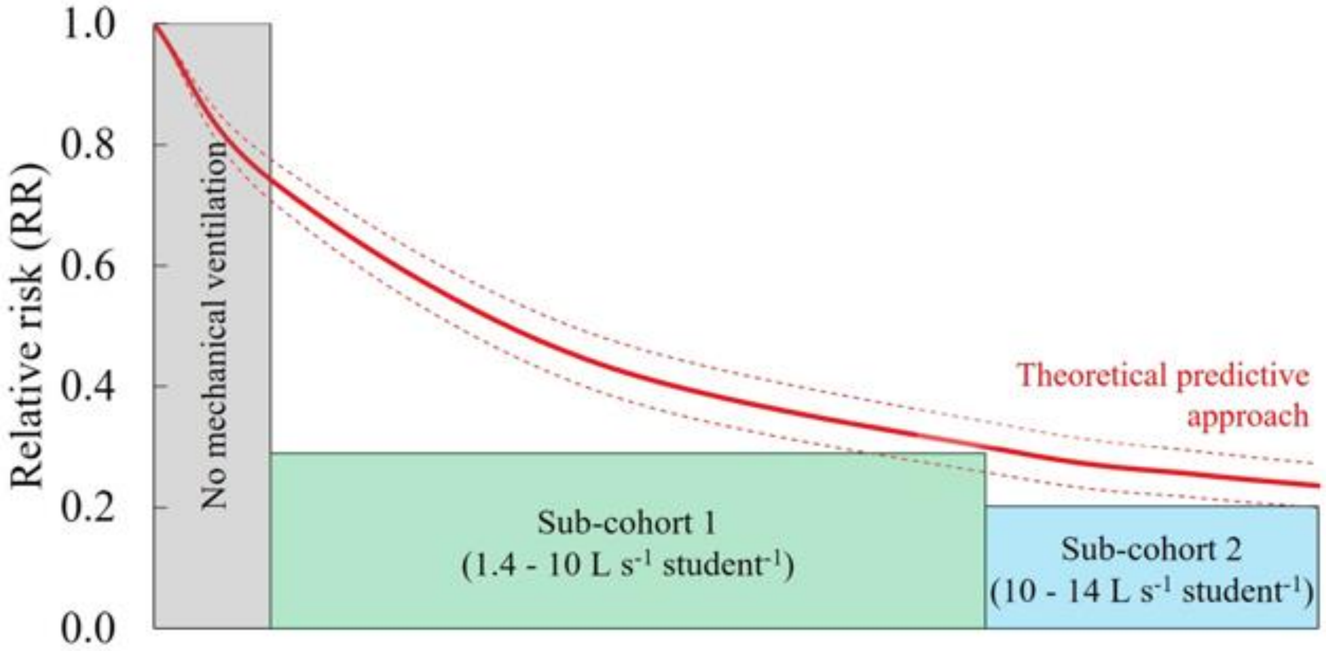
The maximum (nominal) air flow rates of the MVSs installed in the different classrooms ranged between 100 to 1000 $m^3\ h^{-1}$ (with 25th, 50th, and 75th percentiles equal to 360 $m^3\ h^{-1}$, 600 $m^3\ h^{-1}$, and 800 $m^3\ h^{-1}$, respectively) resulting in a ventilation rate per person between 1.4 and 14 $L\ s^{-1}$ $student^{-1}$.

In order to stratify the analysis, we have also introduced two sub-cohorts: i) the sub-cohort 1 represents the classrooms with MVSs characterized by a ventilation rate per person between 1.4 and 10 $L\ s^{-1}$ $student^{-1}$ that meets the standard requirements of indoor air quality, ii) the sub-cohort 2 includes classrooms with a ventilation rate per person $>$10 $L\ s^{-1}$ $student^{-1}$ and up to 14 $L\ s^{-1}$ $student^{-1}$ and it could represent a health-based ventilation to protect from airborne transmission.

Buonanno et al., Increasing ventilation reduces the SARS-CoV-2 airborne transmission in schools: a retrospective cohort study in Italy's Marche region, The Lancet – Infectious diseases, submitted

Parameter	Period of investigation	Classrooms MVS	Classrooms MVS
Incidence cases	Sept. 13th - Dec. 23rd, 2021	1272	18
	Jan. 7th - 31st, 2022	1818	13
	Entire period	3090	31
Incidence (per 1 000	Sept. 13th - Dec. 23rd, 2021	6.3	2.8
	Jan. 7th - 31st, 2022	9.0	2.1
	Entire period	15.3	4.9
Incidence ratio	Sept. 13th - Dec. 23rd, 2021	0.45	
	Jan. 7th - 31st, 2022	0.23	
	Entire period	**0.32**	

Buonanno G, Ricolfi L, Morawska L and Stabile L (2022) Increasing ventilation reduces SARS-CoV-2 airborne transmission in schools: A retrospective cohort study in Italy's Marche region. *Front. Public Health* 10:1087087. doi: 10.3389/fpubh.2022.1087087

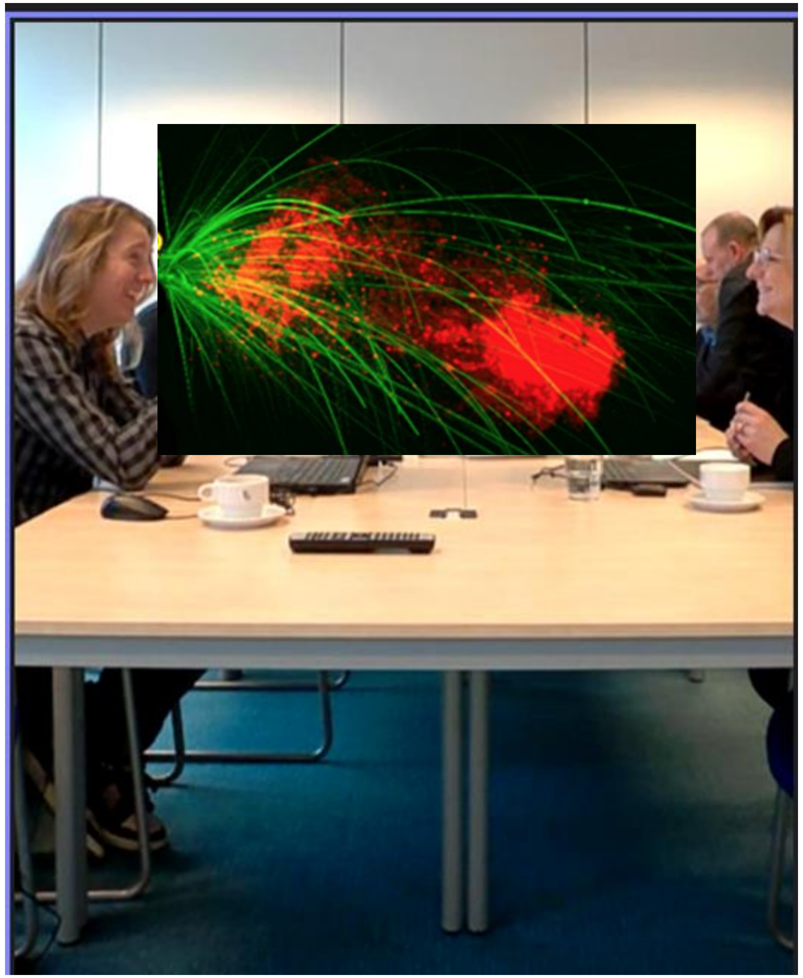


- The agreement between the results obtained from the retrospective cohort study and values calculated through the predictive represents a validation of the approach through a retrospective cohort study.
- Such validations confirm the possibility of extending the use of the approach, once the scenario has been defined, to any indoor environment of interest in addition to school classrooms and providing predictive estimates of the effectiveness of the ventilation for different exposure scenarios and variants of concern.
- The study represents a Halley's comet because we have had simultaneous (i) waves of infections (Delta and Omicron); (ii) different levels of ventilation in school classrooms; and (iii) monitoring of infections.

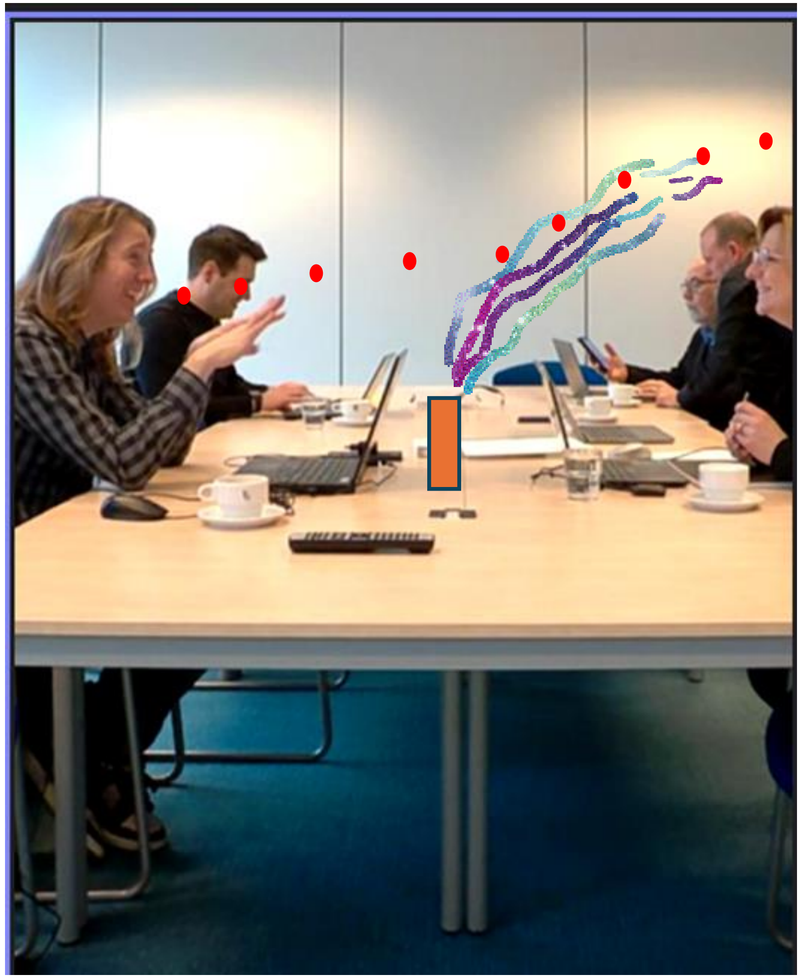
Buonanno G, Ricolfi L, Morawska L and Stabile L (2022) Increasing ventilation reduces SARS-CoV-2 airborne transmission in schools: A retrospective cohort study in Italy's Marche region. *Front. Public Health* 10:1087087. doi: 10.3389/fpubh.2022.1087087

Personal ventilation?

A solution for the short and long range

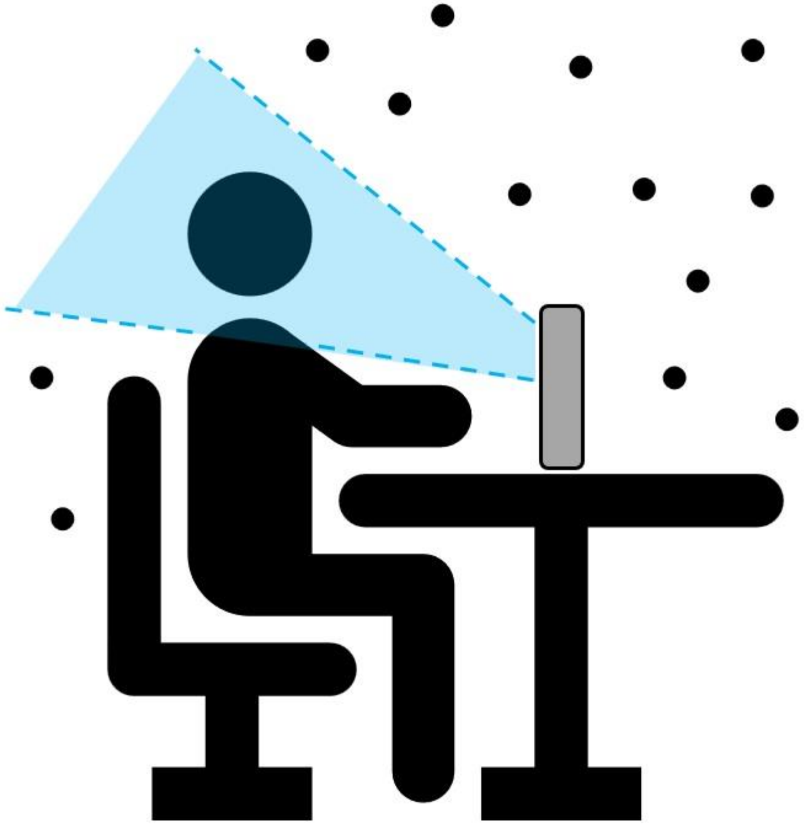


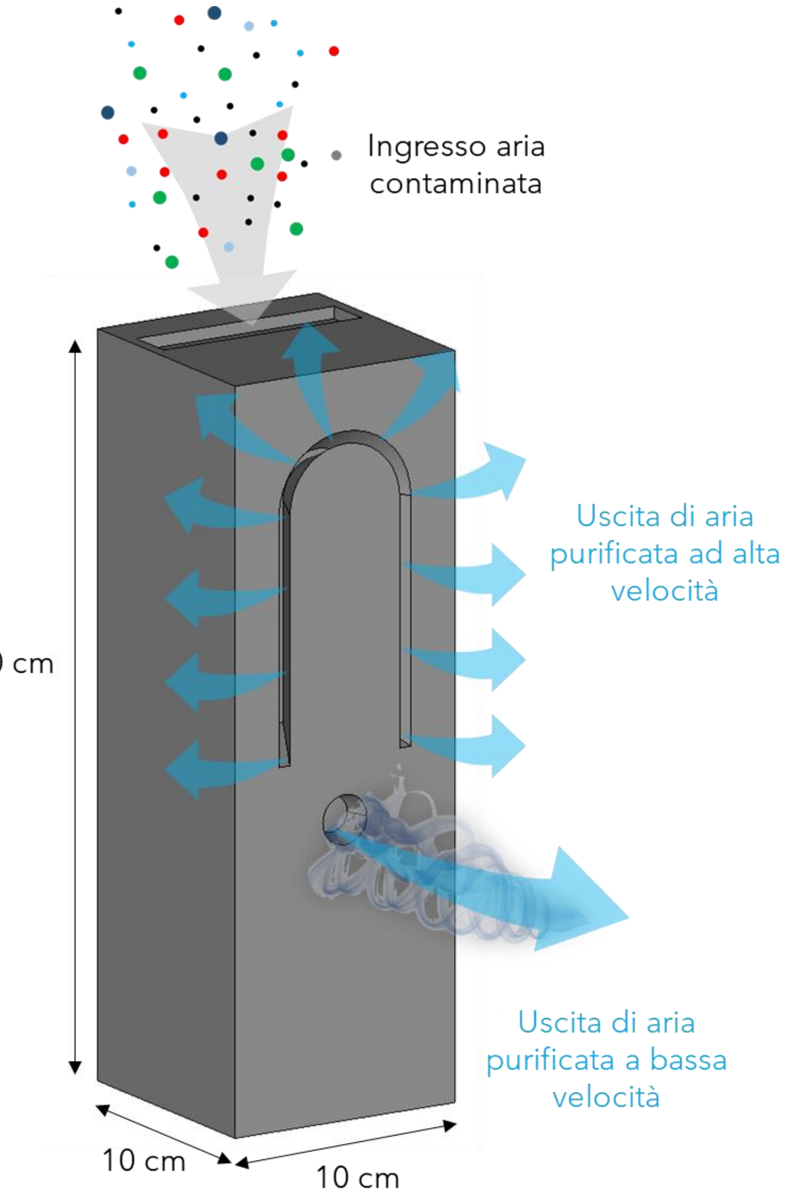
Unprotected from short range airborne transmission



Protected from short range airborne transmi

Personal air cleaner (patent n. 102022000010346)

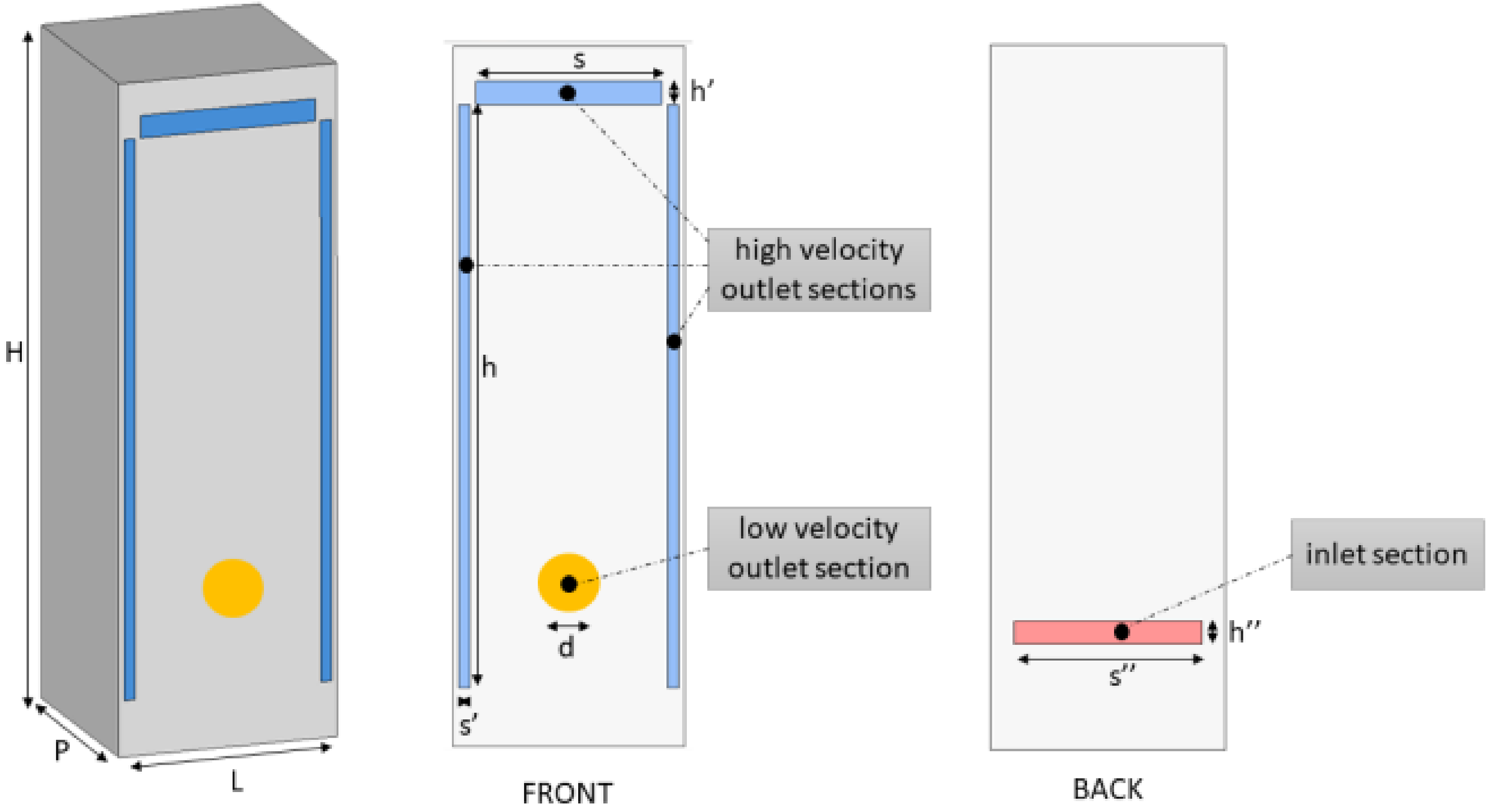




Ingresso aria contaminata

Uscita di aria purificata ad alta velocità

Uscita di aria purificata a bassa velocità

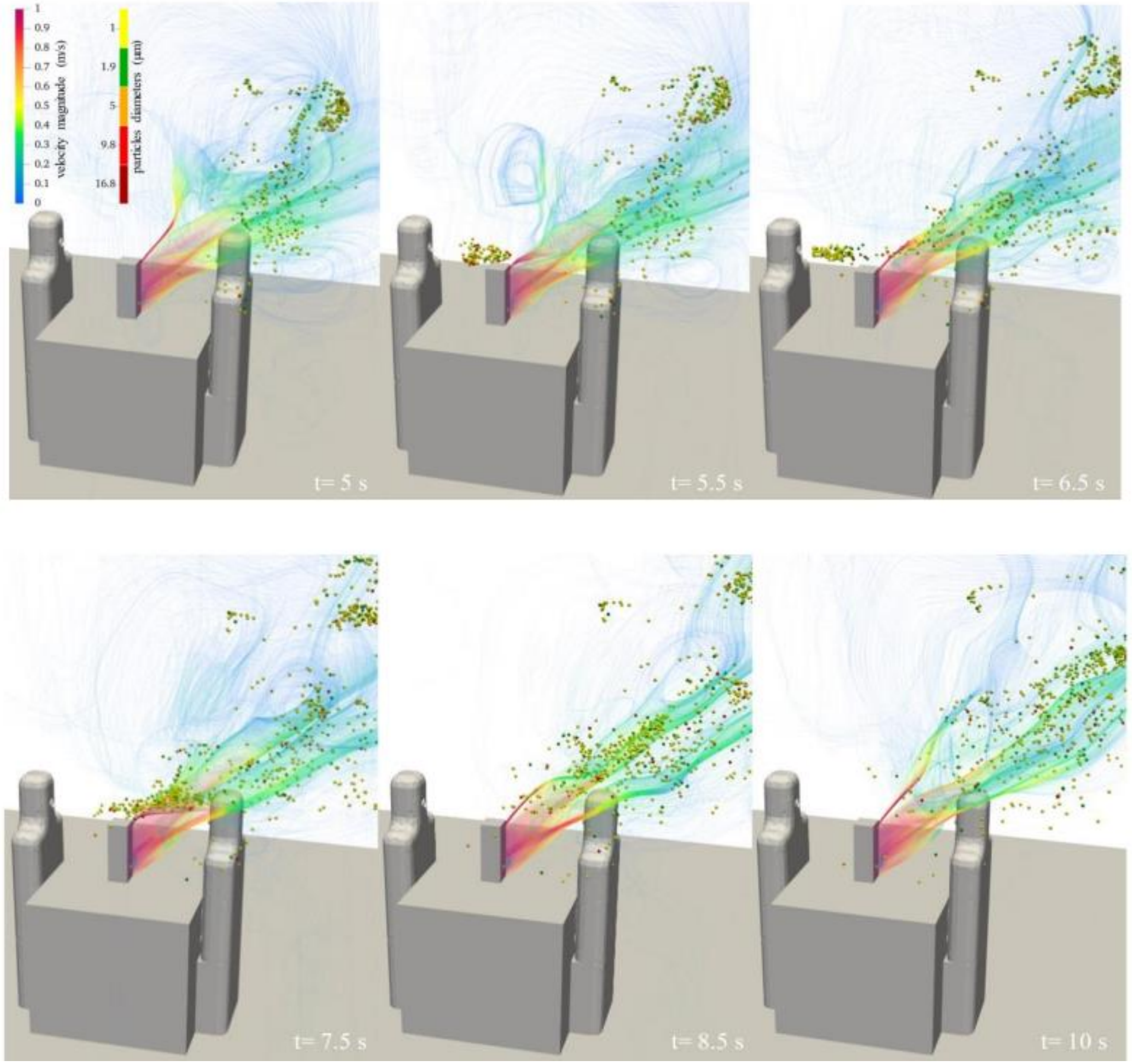


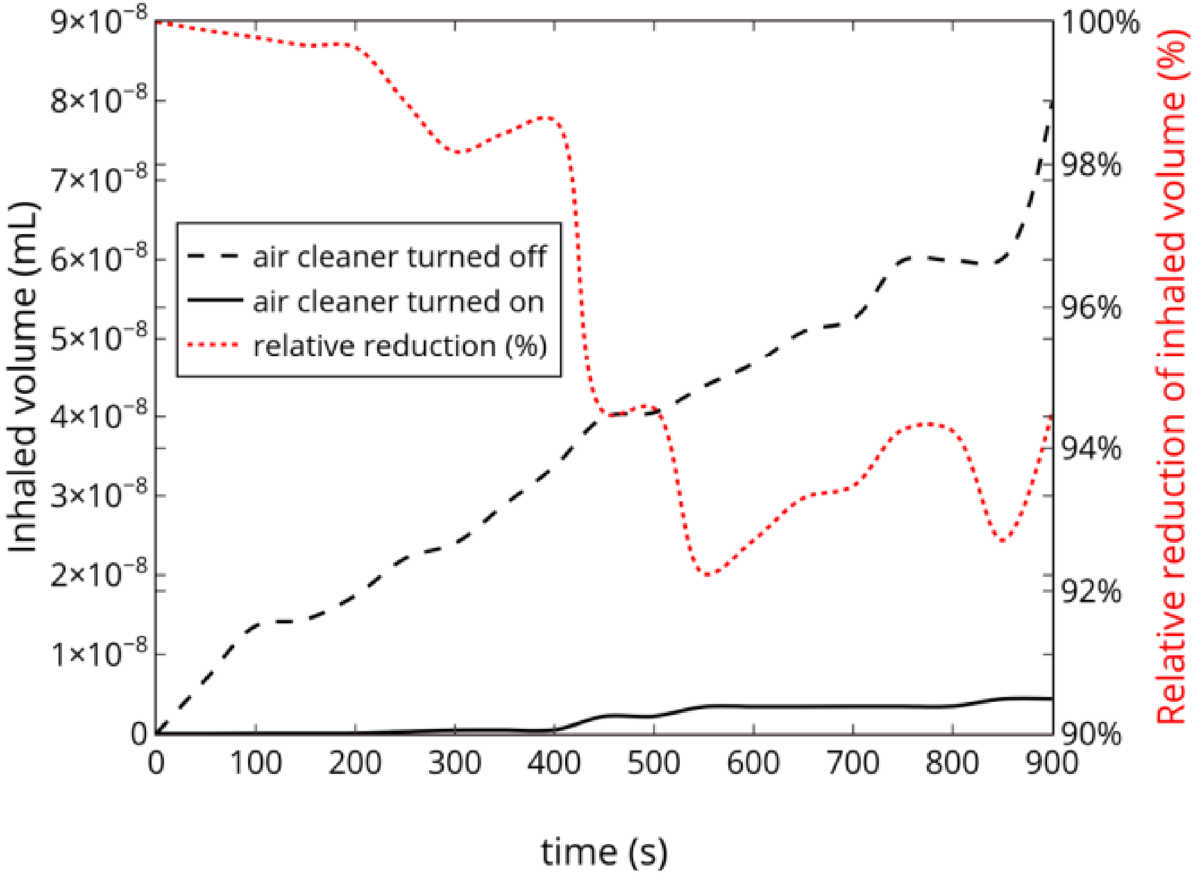
high velocity outlet sections

low velocity outlet section

inlet section

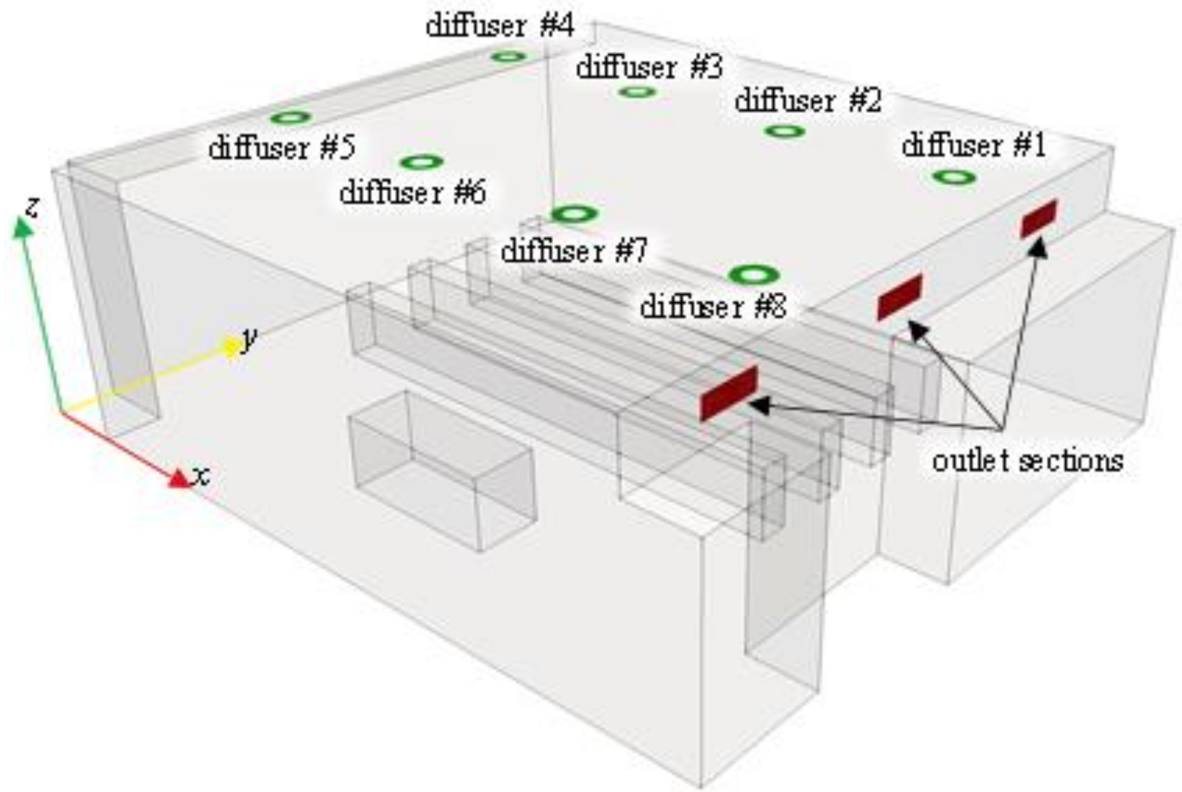
Reducing the short range risk

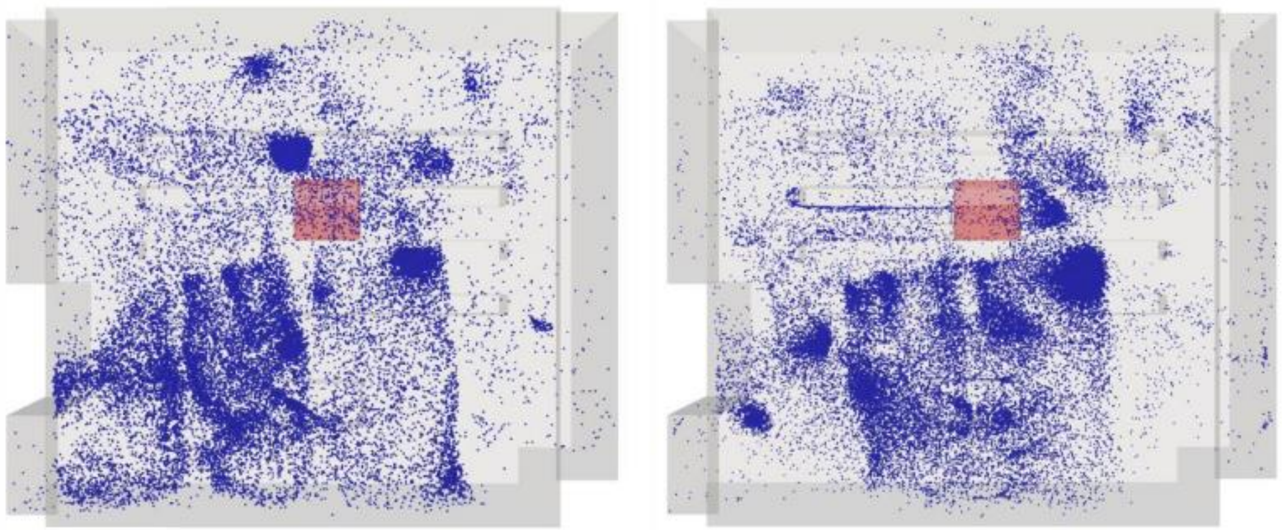




Cortellessa G., Canale C., Stabile L., Grossi G., Buonanno G., Arpino F., 2023. Effectiveness of a portable personal air cleaner in reducing the airborne transmission of respiratory pathogens. Buildings and Environment, under review

Case study 3: meeting room/university classroom

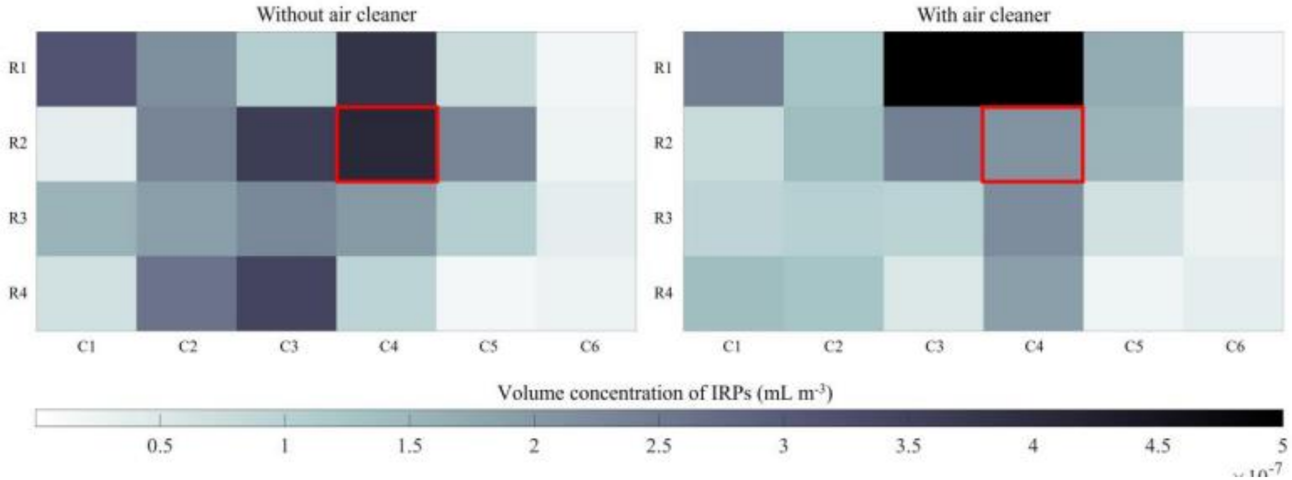




Without air cleaner

With air cleaner

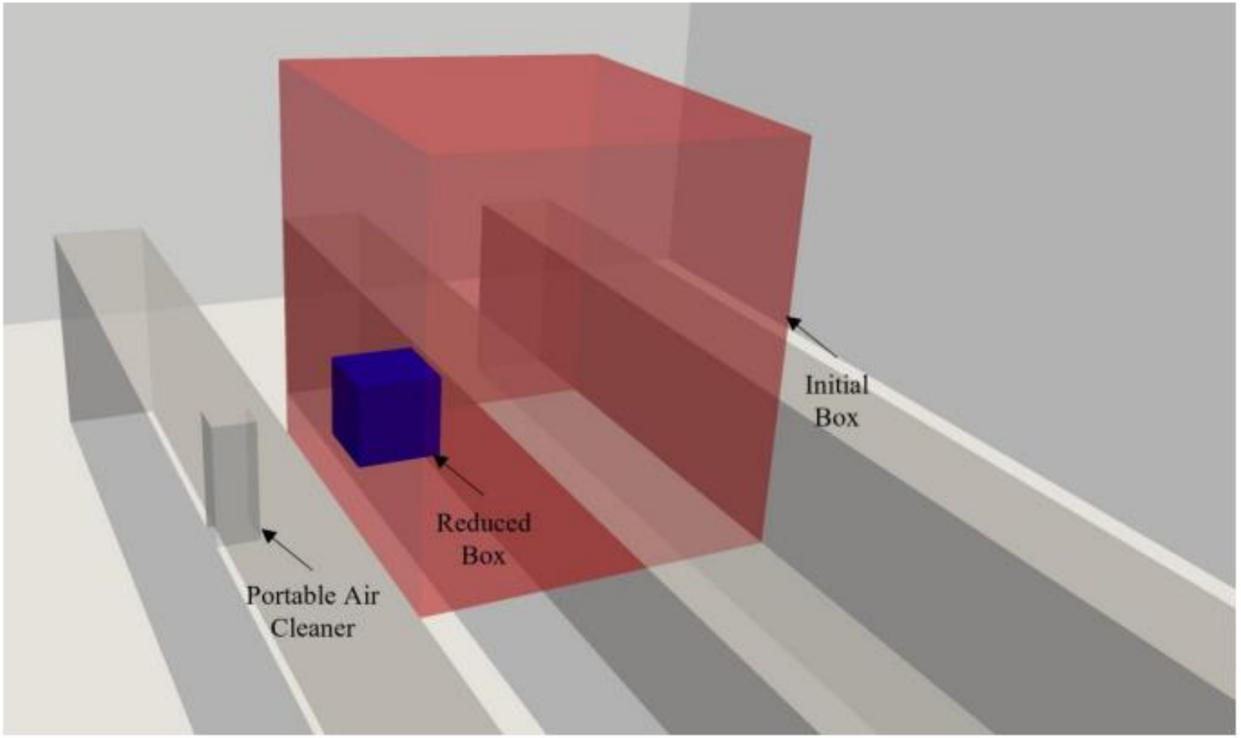
Figure 15 – Top view of the spatial distribution of IRPs in the lecture room with and without personal air cleaner.

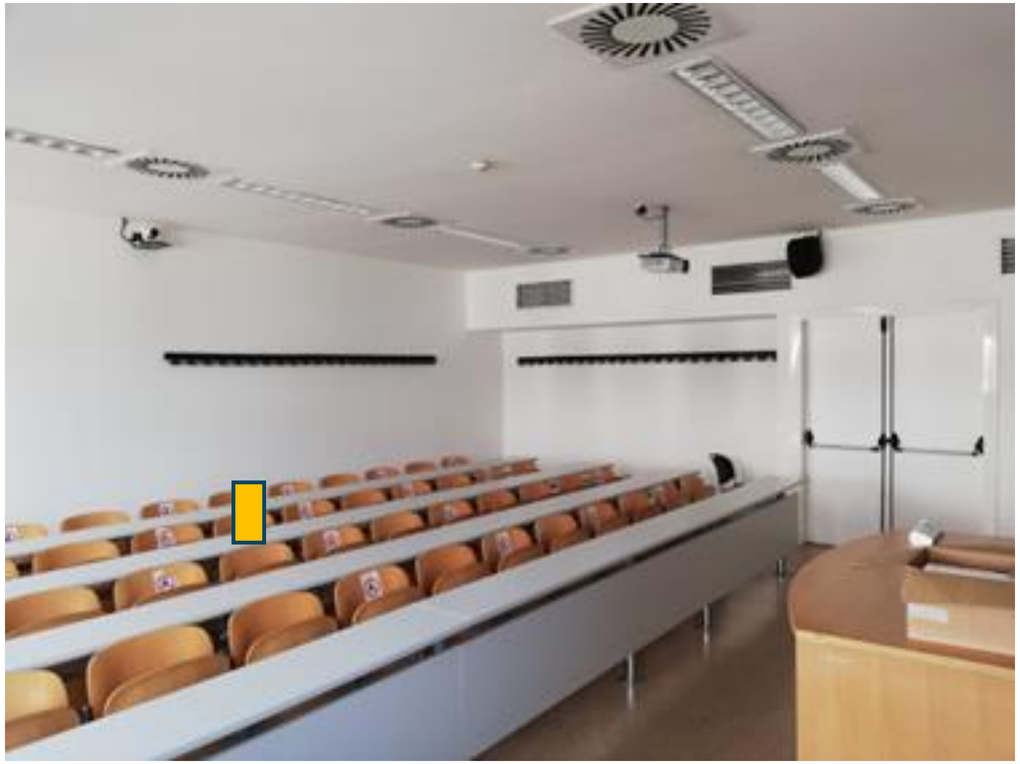


Without air cleaner

With air cleaner

Meeting room/university classroom



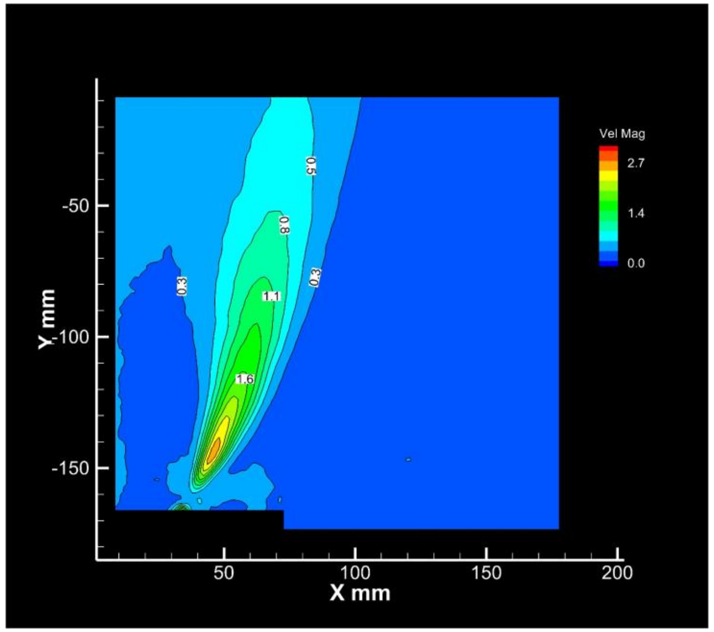


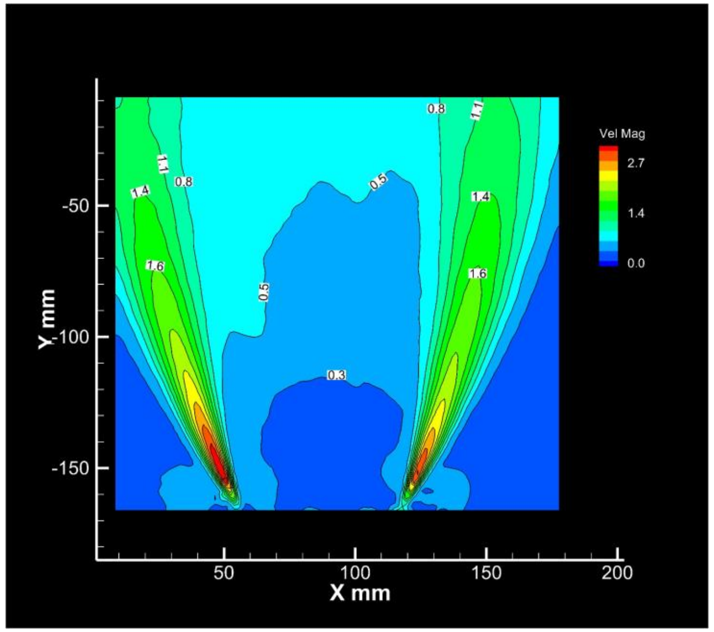
Box	Volume concentration of infectious respiratory particles (mL m^{-3})		Relative reduction of volume concentration
	without device	with device	
Initial box (1.00×1.00×0.88 m)	4.07×10^{-7}	2.08×10^{-7}	49.1%
Reduced box (0.20×0.20×0.20 m)	1.25×10^{-6}	5.95×10^{-9}	99.5%

Prototype 2.0

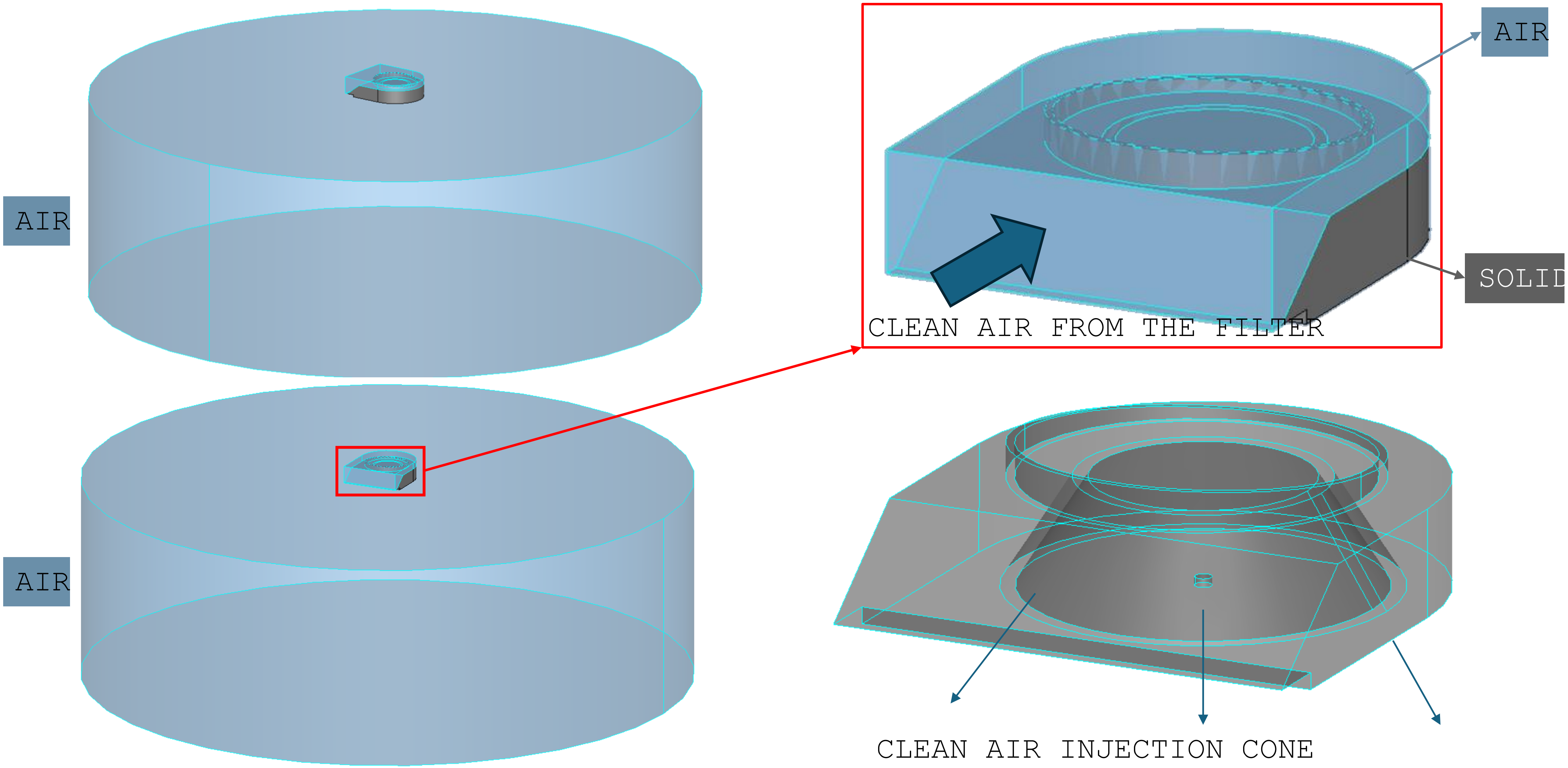
The prototype 2.0 is more compact, with dimensions of 10 x 10 x 20 cm.

The thickness of the air jet openings has been reduced to 2 mm, allowing an expected air jet velocity at the openings of 5-6 m/s.

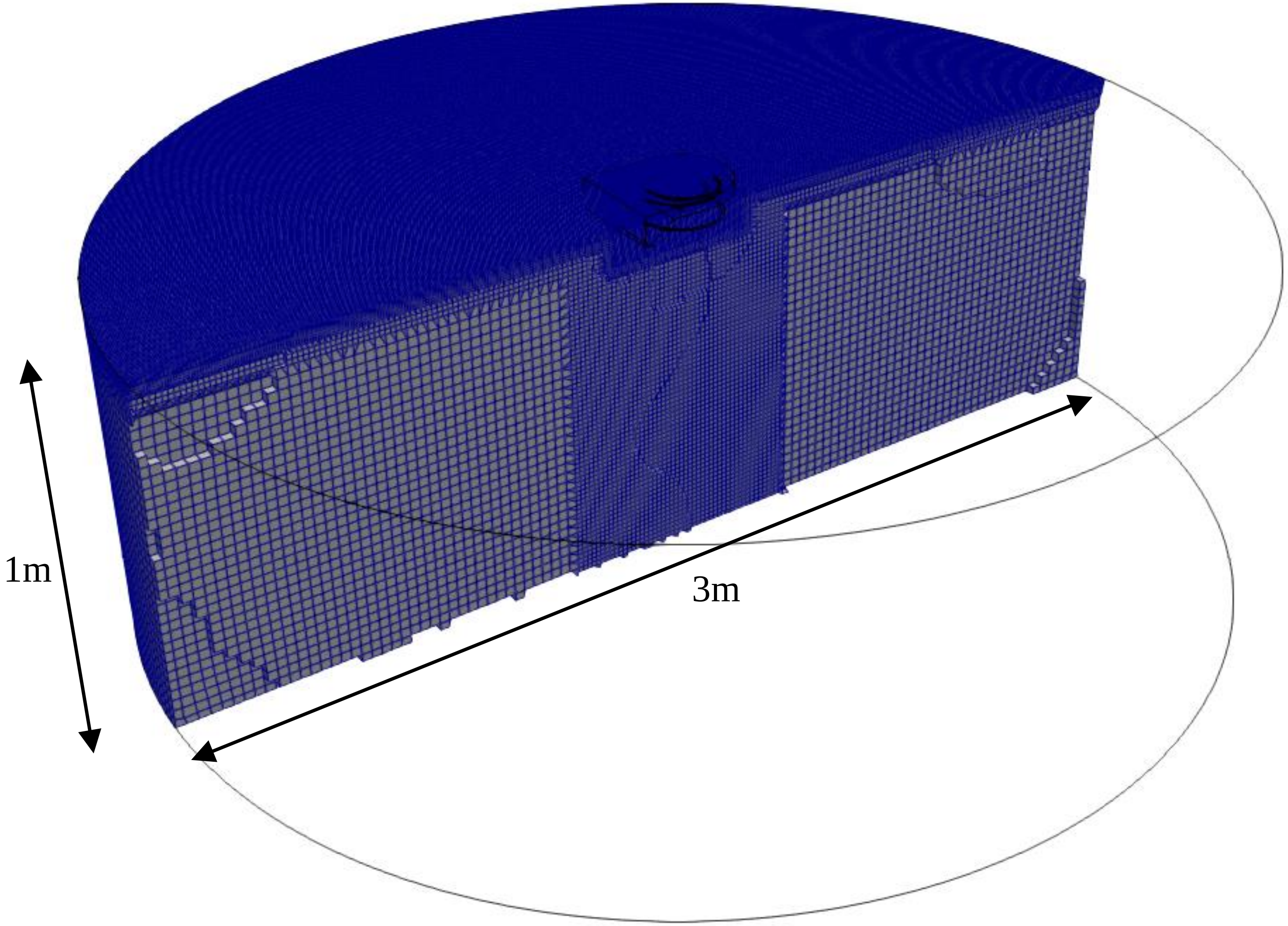




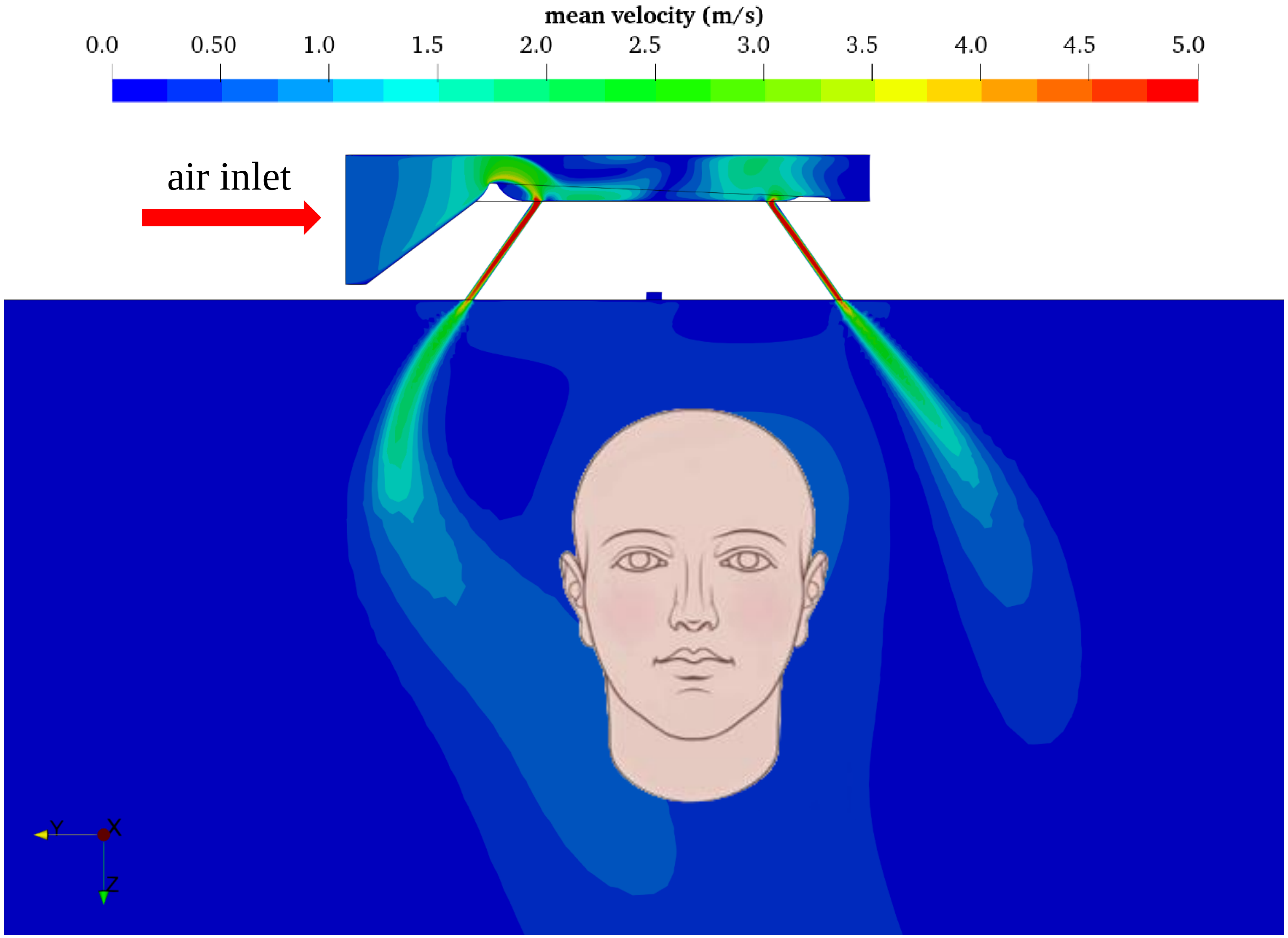
Geometry


AIR
AIR
AIR
SOLID
CLEAN AIR FROM THE FILTER
CLEAN AIR INJECTION CONE

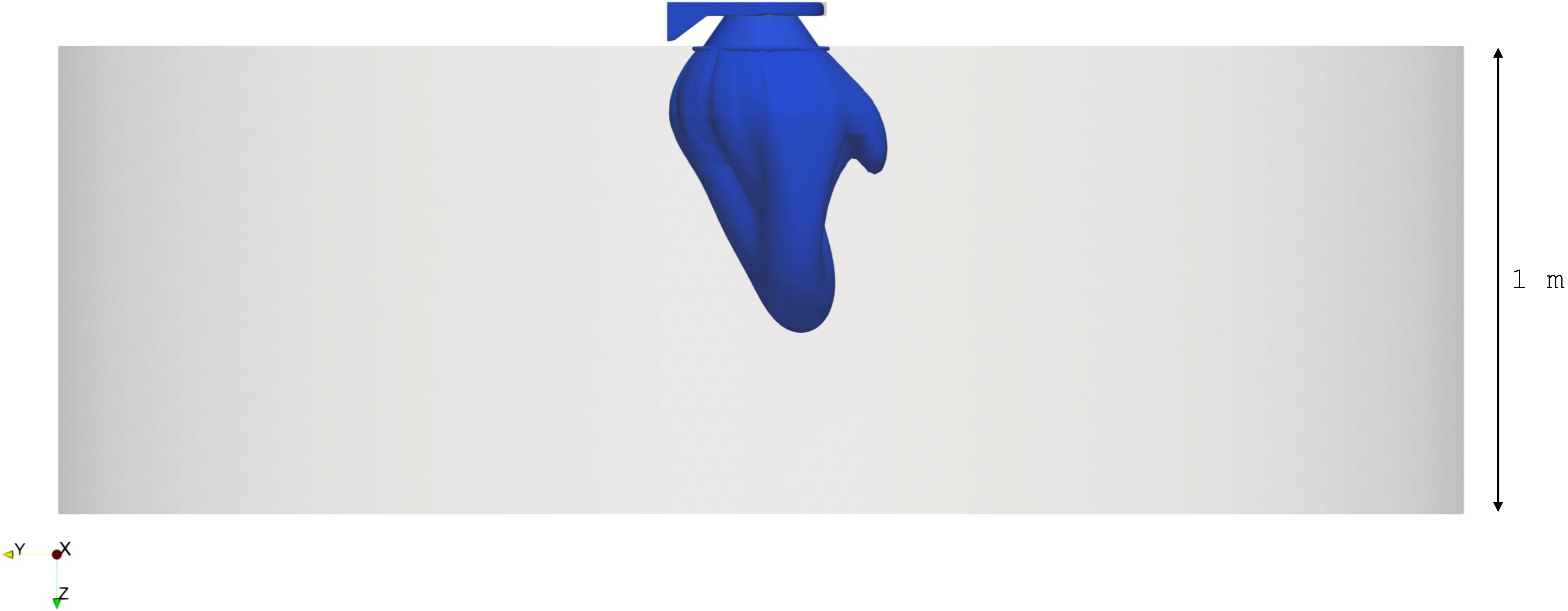
Mesh



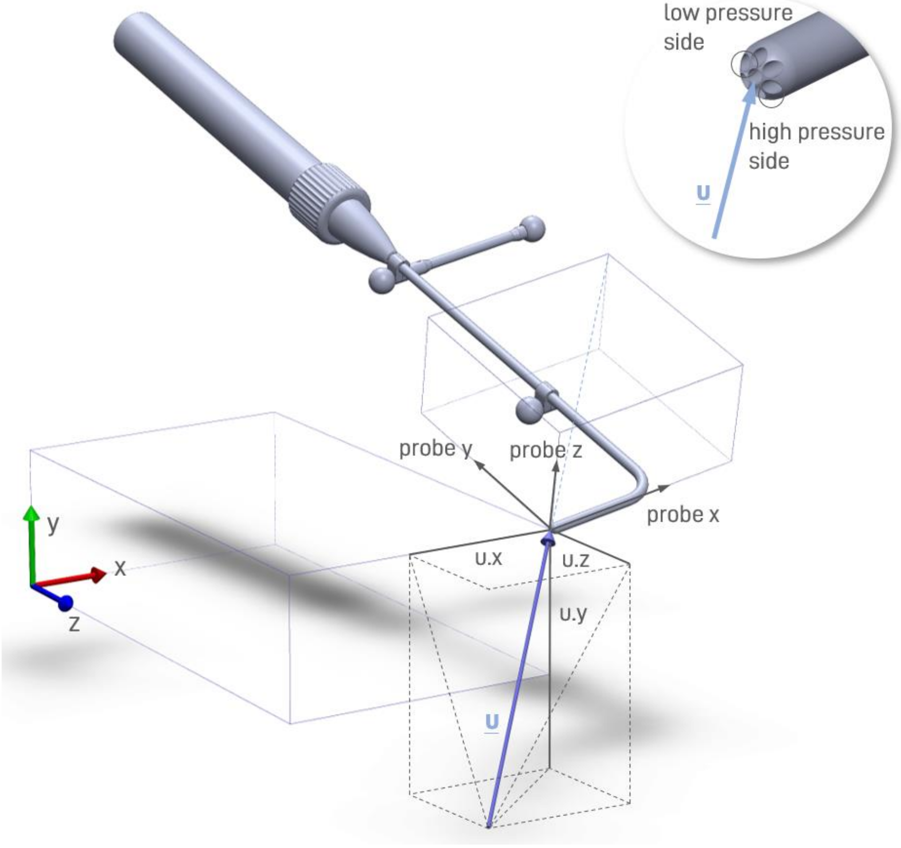
Computational grid composed by 7.9 millions of cells

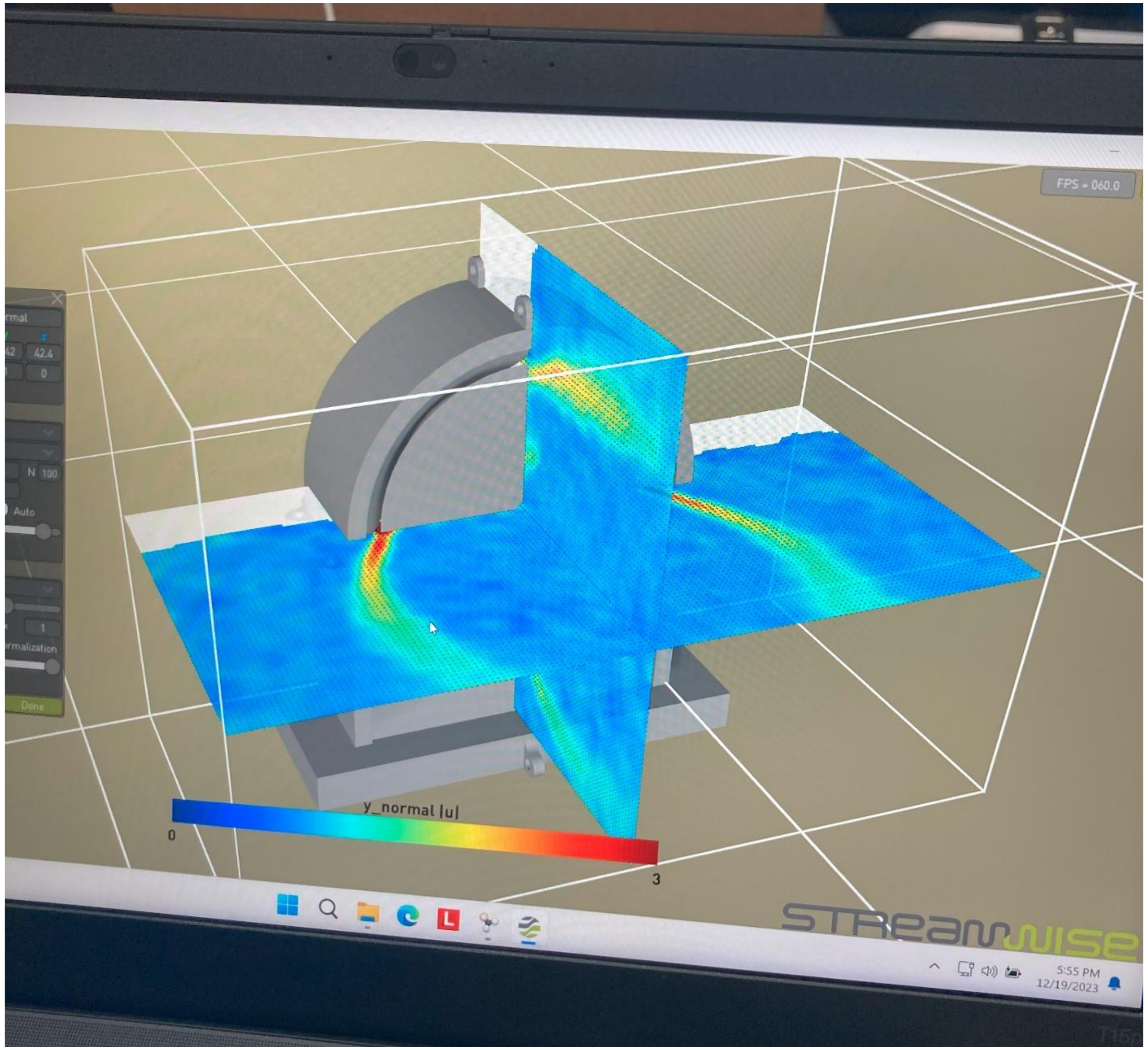

mean velocity (m/s)
0.0
0.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
air inlet
Y
X
Z

Iso-surface at 0.3 m/s



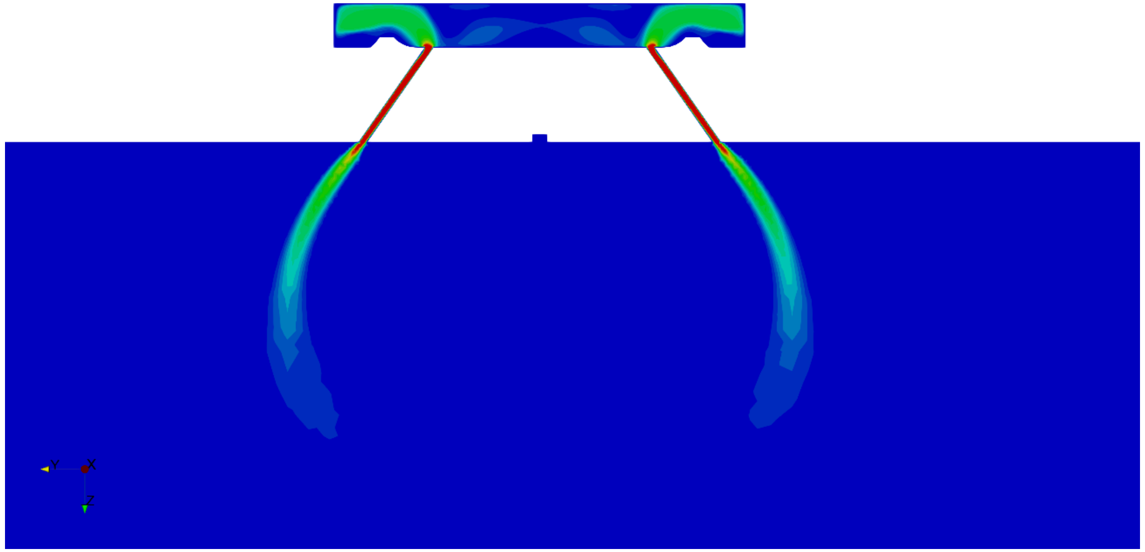
5-hole pressure probe measurements (ProCap Streamwise)



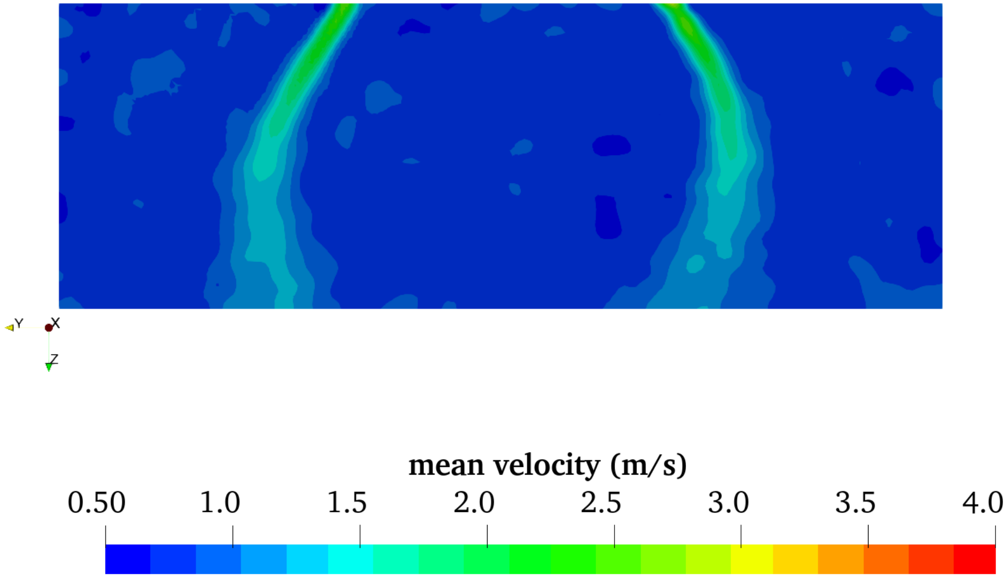

FPS = 060.0
y_normal |u|
0
3
STREAMWISE
5:55 PM
12/19/2023

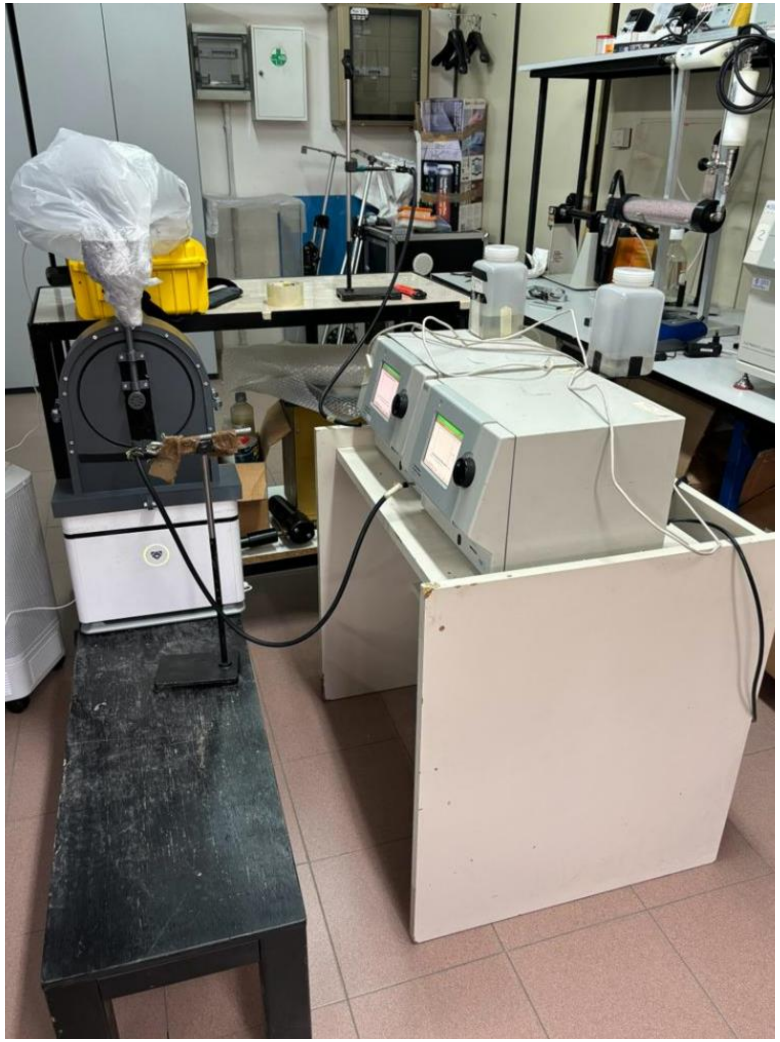
Experimental-numerical comparison (x-normal surface)

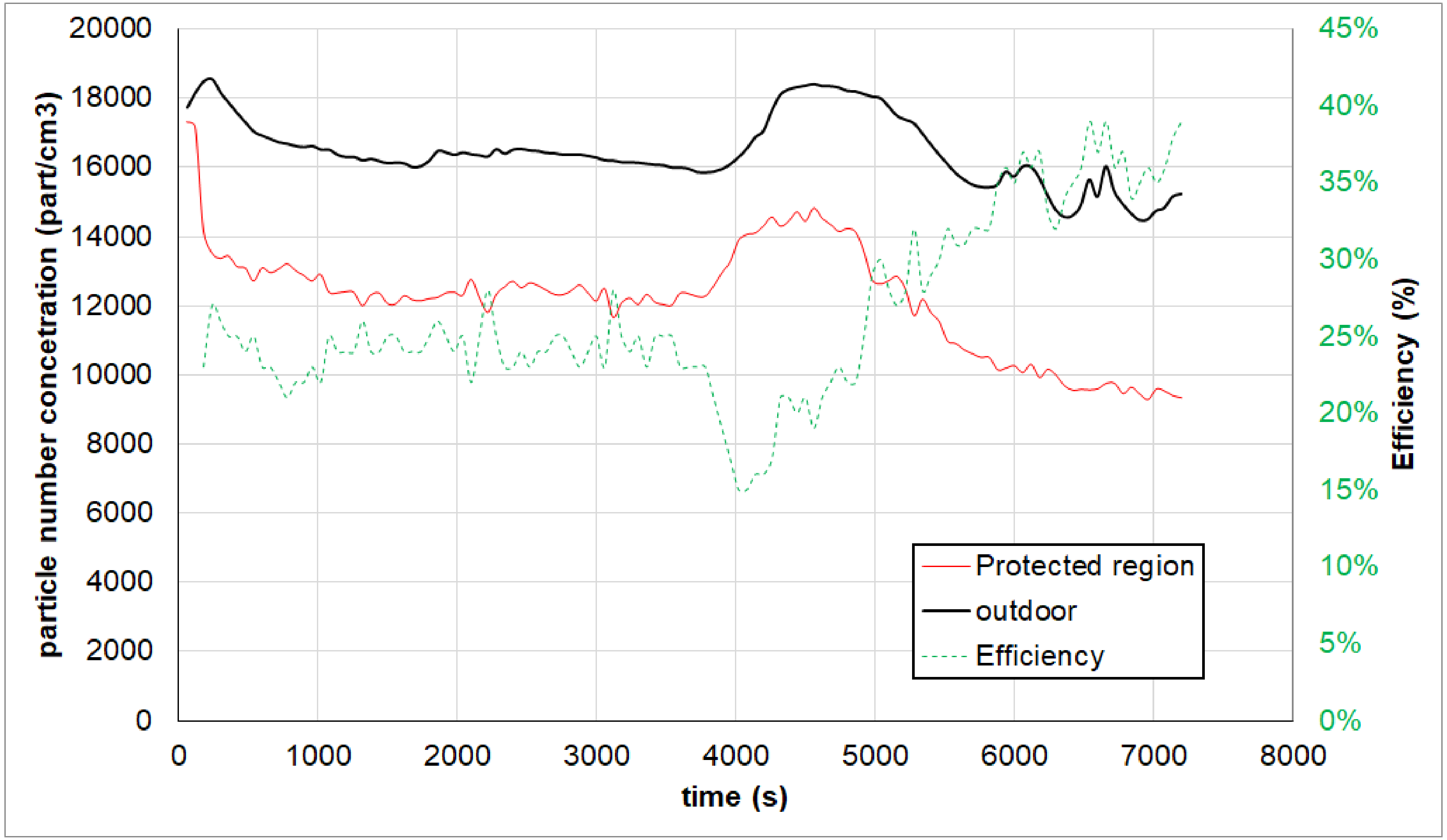
CFD



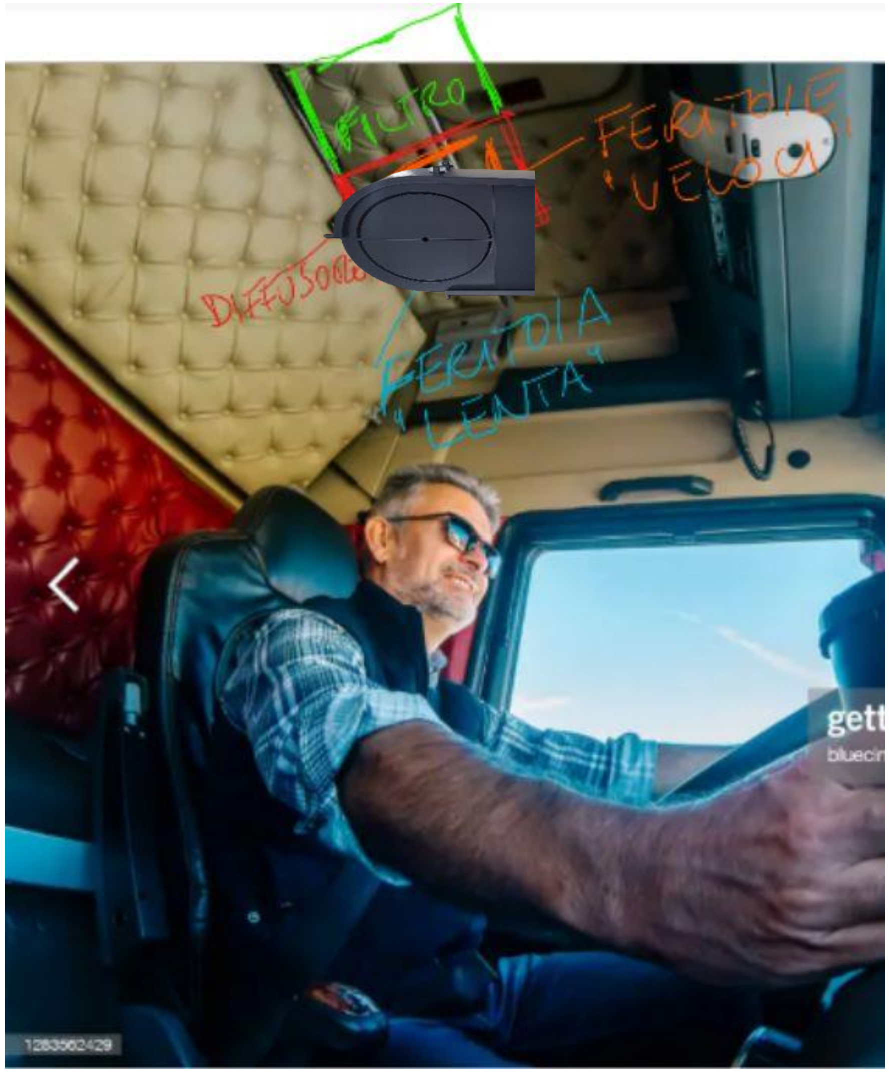
5-hole pressure probe






particle number concetration (part/cm3)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
0
1000
2000
3000
4000
5000
6000
7000
8000
time (s)
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
Efficiency (%)
Protected region
outdoor
Efficiency


WELCOME BACK TO SCHOOL!


FILTRO
FERITOIE "VELOCI"
DIFFUSORE
FERITOIA "LENTA"

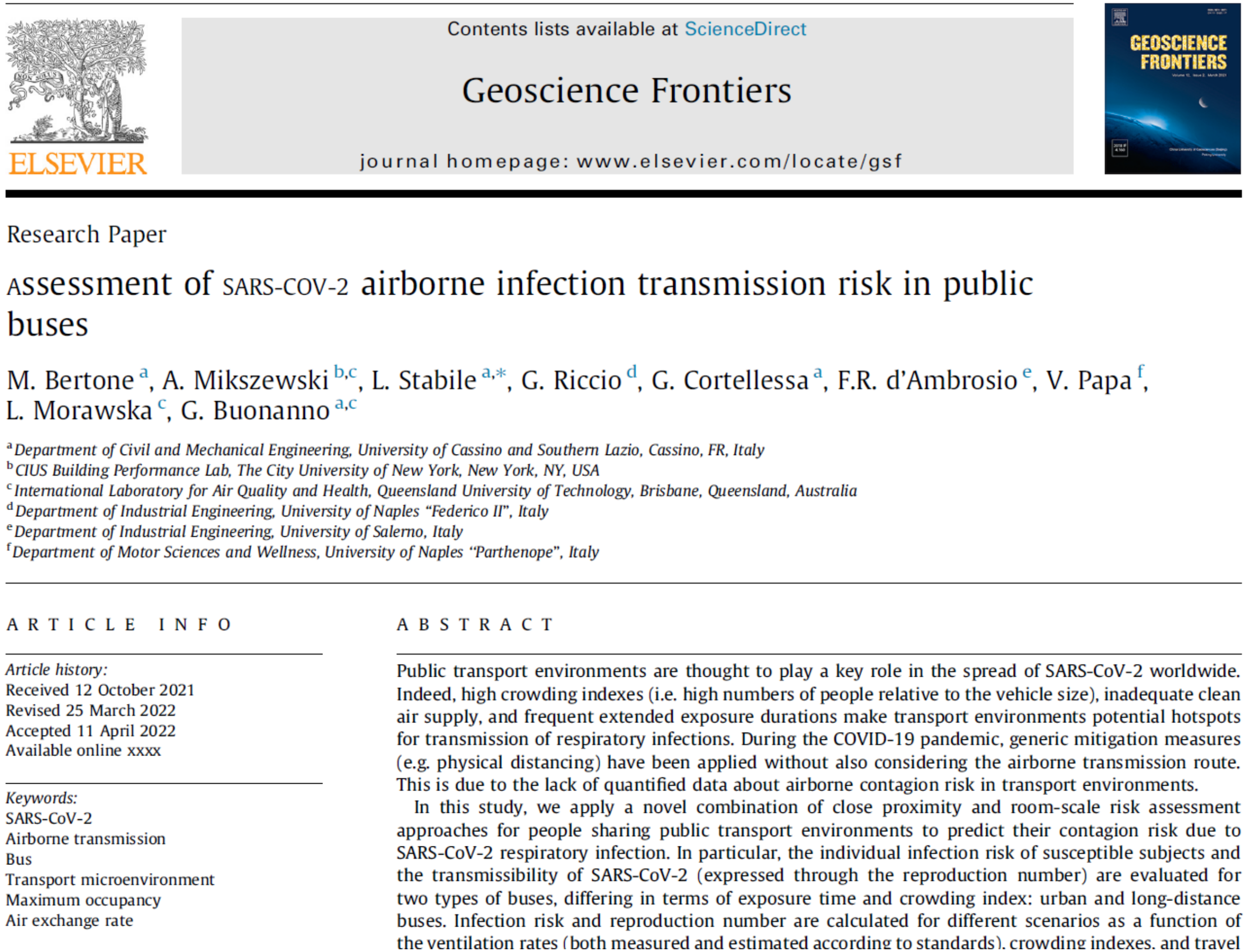
We can assess short and long range airborne transmission of respiratory pathogens

We can manage short and long range infectious risk through engineering controls as ventilation and air distribution

Car cabin

Airborne transmission in transport microenvironment: high occupancy and the possible inadequate ventilation.

Can we adopt simplified models to assess the infectious risk?



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Research Paper

Assessment of SARS-CoV-2 airborne infection transmission risk in public buses

M. Bertone [a], A. Mikszewski [b,c], L. Stabile [a,*], G. Riccio [d], G. Cortellessa [a], F.R. d'Ambrosio [e], V. Papa [f], L. Morawska [c], G. Buonanno [a,c]

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[b] *CIUS Building Performance Lab, The City University of New York, New York, NY, USA*
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[d] *Department of Industrial Engineering, University of Naples "Federico II", Italy*
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Airborne transmission
Bus
Transport microenvironment
Maximum occupancy
Air exchange rate

ABSTRACT

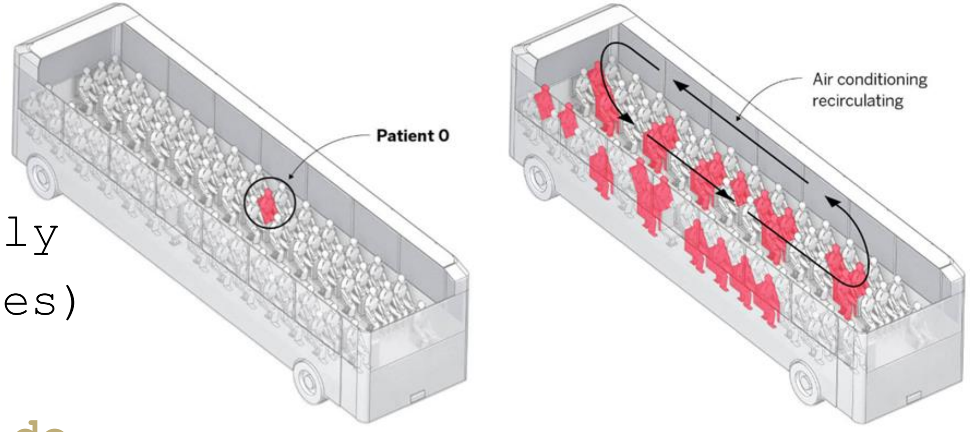
Public transport environments are thought to play a key role in the spread of SARS-CoV-2 worldwide. Indeed, high crowding indexes (i.e. high numbers of people relative to the vehicle size), inadequate clean air supply, and frequent extended exposure durations make transport environments potential hotspots for transmission of respiratory infections. During the COVID-19 pandemic, generic mitigation measures (e.g. physical distancing) have been applied without also considering the airborne transmission route. This is due to the lack of quantified data about airborne contagion risk in transport environments.

In this study, we apply a novel combination of close proximity and room-scale risk assessment approaches for people sharing public transport environments to predict their contagion risk due to SARS-CoV-2 respiratory infection. In particular, the individual infection risk of susceptible subjects and the transmissibility of SARS-CoV-2 (expressed through the reproduction number) are evaluated for two types of buses, differing in terms of exposure time and crowding index: urban and long-distance buses. Infection risk and reproduction number are calculated for different scenarios as a function of the ventilation rates (both measured and estimated according to standards), crowding indexes, and travel

Introduction: transport microenvironments

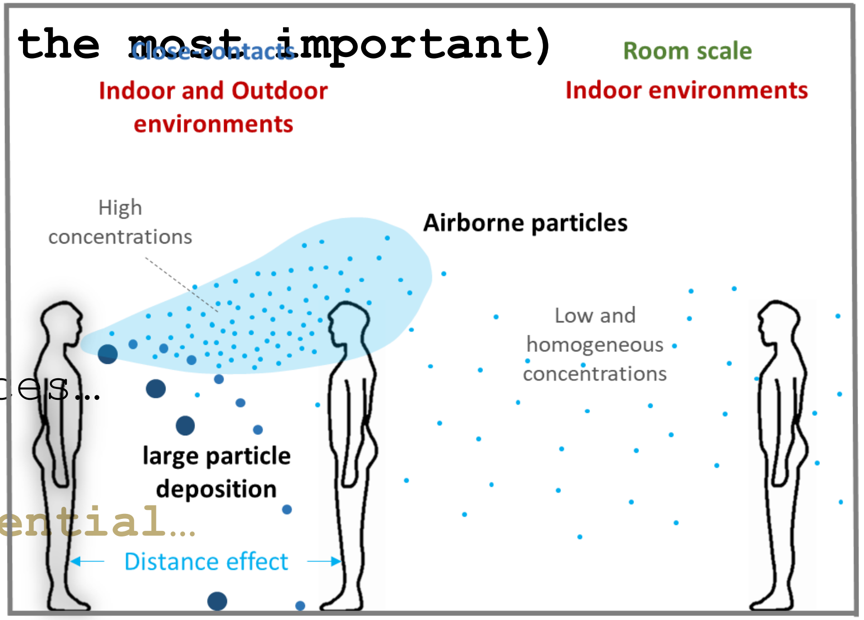
Transport microenvironments

- several outbreaks worldwide
- high crowding indexes
- inadequate clean (pathogen-free) air supply
- no existing ventilation standard (for buses)



Generic mitigation measures applied worldwide

- **Not considering the airborne transmission (i.e. the most important)**
- sanification,
- social distancing,
- reduced occupancy (50%, 75%, 80% …)
- masking,
- varying start and end times of schools and offices…



Quantify the risk of airborne transmission is essential…

Aims of the work

Aims of the work

- quantifying the risk of airborne transmission in buses
- identifying mitigation strategies to reduce the transmission potential of SARS-CoV-2 infection for safe transportation of passengers and to control the spread of the pandemic.

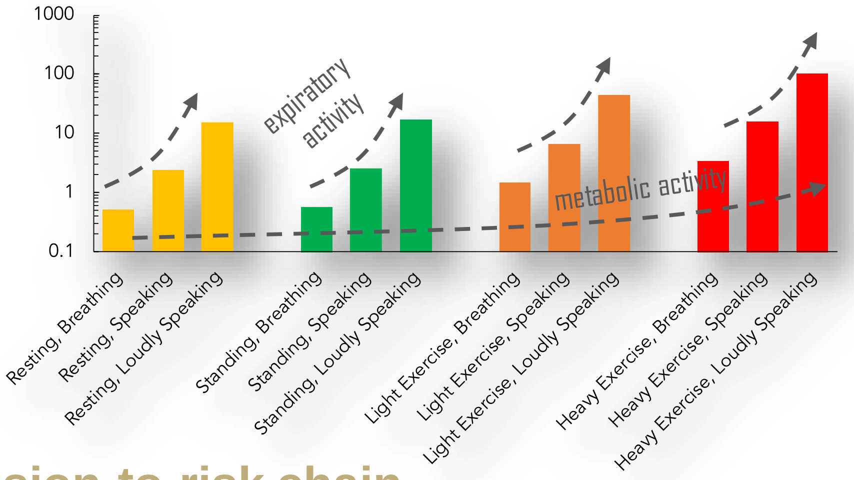
How…

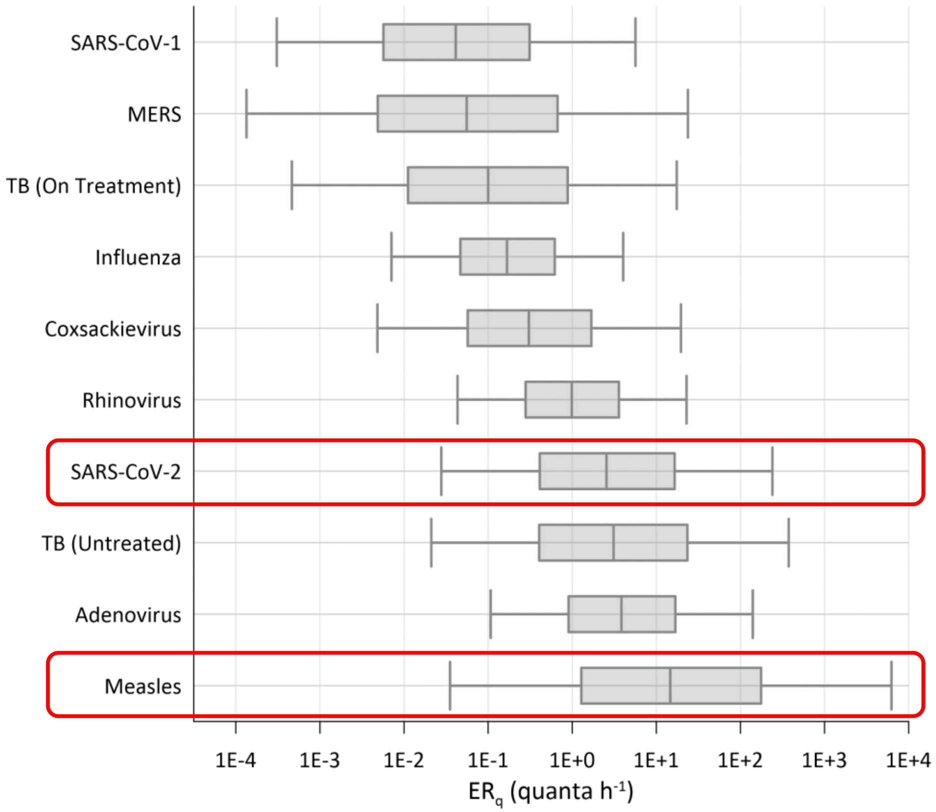
- applying a combination of **close proximity** and **room-scale** risk assessment approaches for people sharing public transport environments
- evaluating the **individual infection risk** of susceptible subjects and the transmissibility of SARS-CoV-2 (expressed through the **reproductive number**)
- two types of buses, differing in terms of exposure time and crowding index, **urban** and **long-distance** buses
- different scenarios as a function of the **ventilation rates** (both measured and estimated according to standards), crowding indexes, and travel times

Methodology: quantifying the viral emission

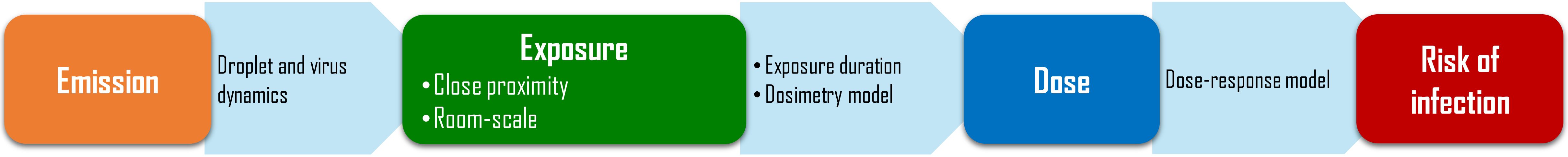
Viral emission approach (Buonanno, Morawsk

- Droplet volume emission (expiratory acti
- Expiration flow rate (metabolic activity
- Viral load & Minimum infectious dose





Emission-to-risk chain



Methodology: emission-to-risk approach

CFD approach: close-proximity risk (Cortellessa et al., 2021)

Risk resulting from inhaling virus-laden airborne particles within
subject

Exposure to virus-laden particles (after evaporation)

Estimated from CFD simulations, distance effect

Dose received by exposed persons

$$D(c_v) = \frac{c_v \cdot V_{d-airborne-pre} \cdot T}{\mathrm{HID}_{63}}$$

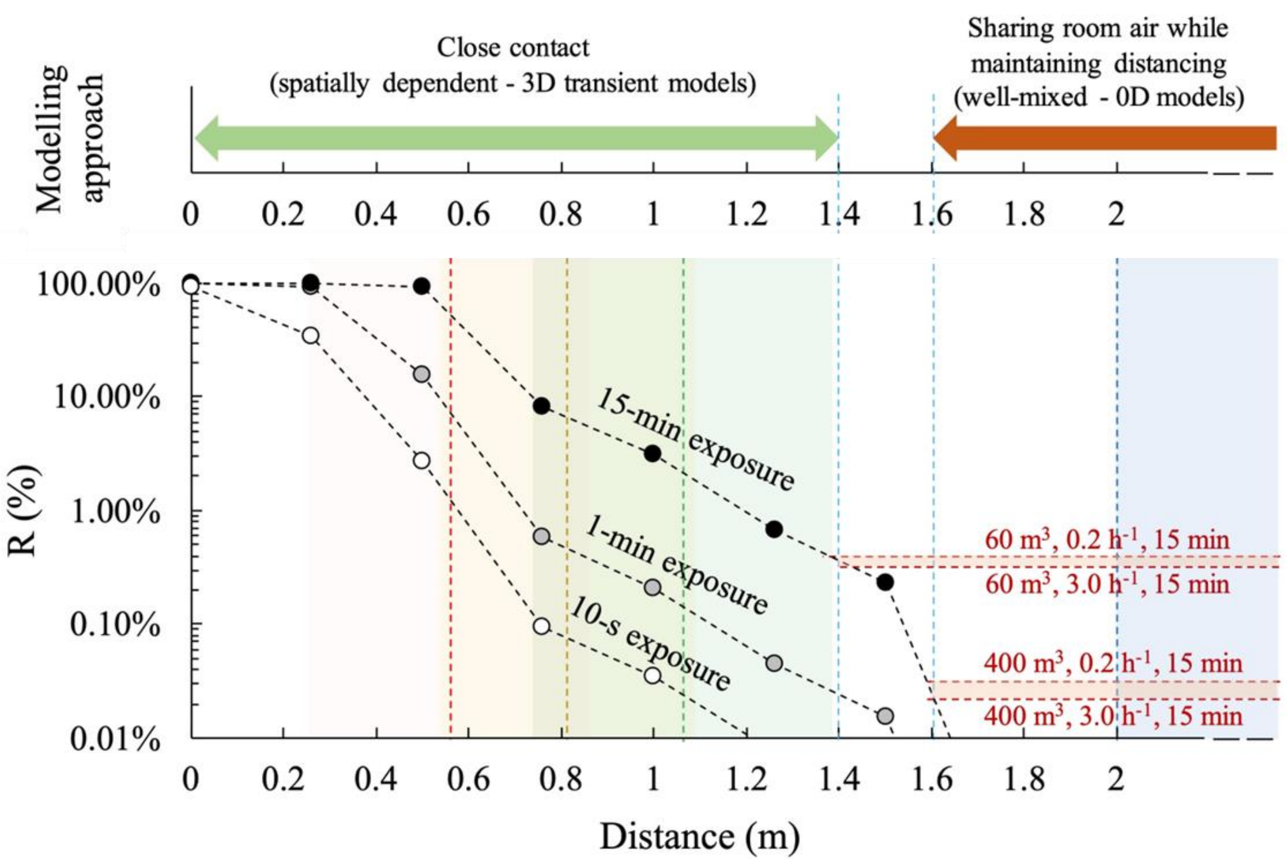
Risk of infection

$$P_I(c_v) = 1 - e^{-D(c_v)}$$

$$IR_{cp} = \int_{ER_q} \left(P_I(c_v) \cdot P_{c_v}\right) dc_v$$

Basic reproductive number – secondary cases

$$R_{cp} = IR_{cp}$$



Methodology: emission-to-risk approach

Box-model approach: room-scale risk (Buonanno, Stabile, Morawska 2020)

Virus-laden droplet dynamics in indoor environments: an indoor air quality

Exposure to viral concentration $n(t)$

$$n(t, ER_q) = \frac{ER_q}{(AER + k + \lambda) \cdot V} \cdot \left(1 - e^{-(AER+k+\lambda)\cdot t}\right)$$

Dose received by exposed persons

$$D_q = IR \int_0^T n(t, ER_q)dt$$

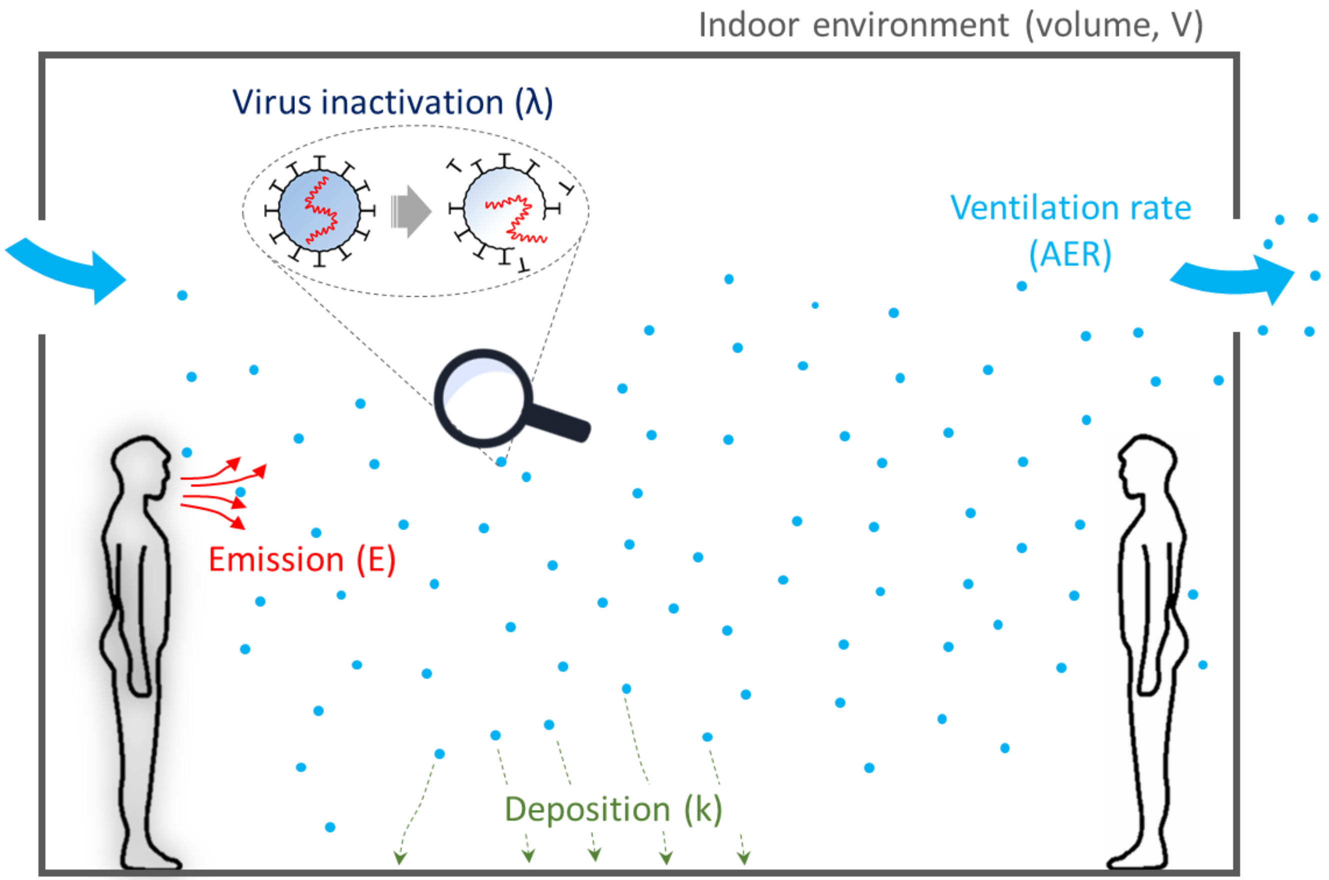
Risk of infection

$$P_I\left(ER_q\right) = 1 - e^{-D_q\left(ER_q\right)} \quad (\%)$$

$$IR_{rs} = \int_{ER_q} \left(P_I(ER_q) \cdot P_{ER_q}\right) dER_q$$

Basic reproductive number & maximum occupancy

$$R_{rs} = IR_{rs} \cdot S \qquad MRO = \frac{1 - IR_{cp}}{IR_{rs}}$$



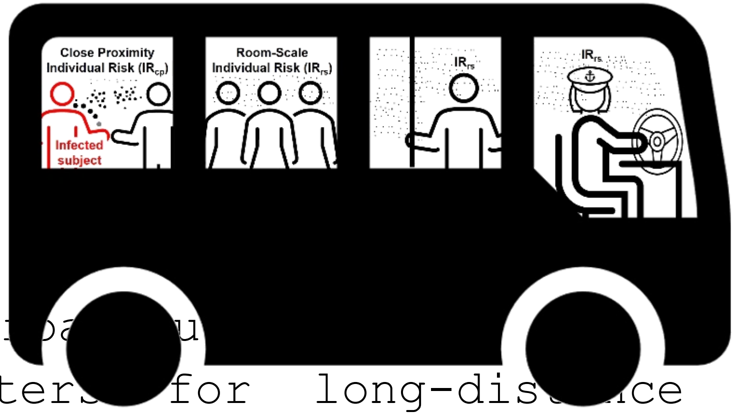
Methodology: scenarios & influence parameters

Urban and long-range buses

Characteristics of the buses

Bus class	Maximum occupancy, ECE-R107, 2015 regulation			Volume (m^3)	Crowding index (person m^{-3})	Total HVAC system flow rate, recirculated+fresh air (m^3 h^{-1})	Air exchange rate due to outdoor fresh air for rolling stock (EN 1432-1) (h^{-1})
	Seats	Standees	Tot				
I – Urban	36	57	93	63	1.5	4400	22
III – Long-distance	51	-	51	65	0.8		12

Influence parameters



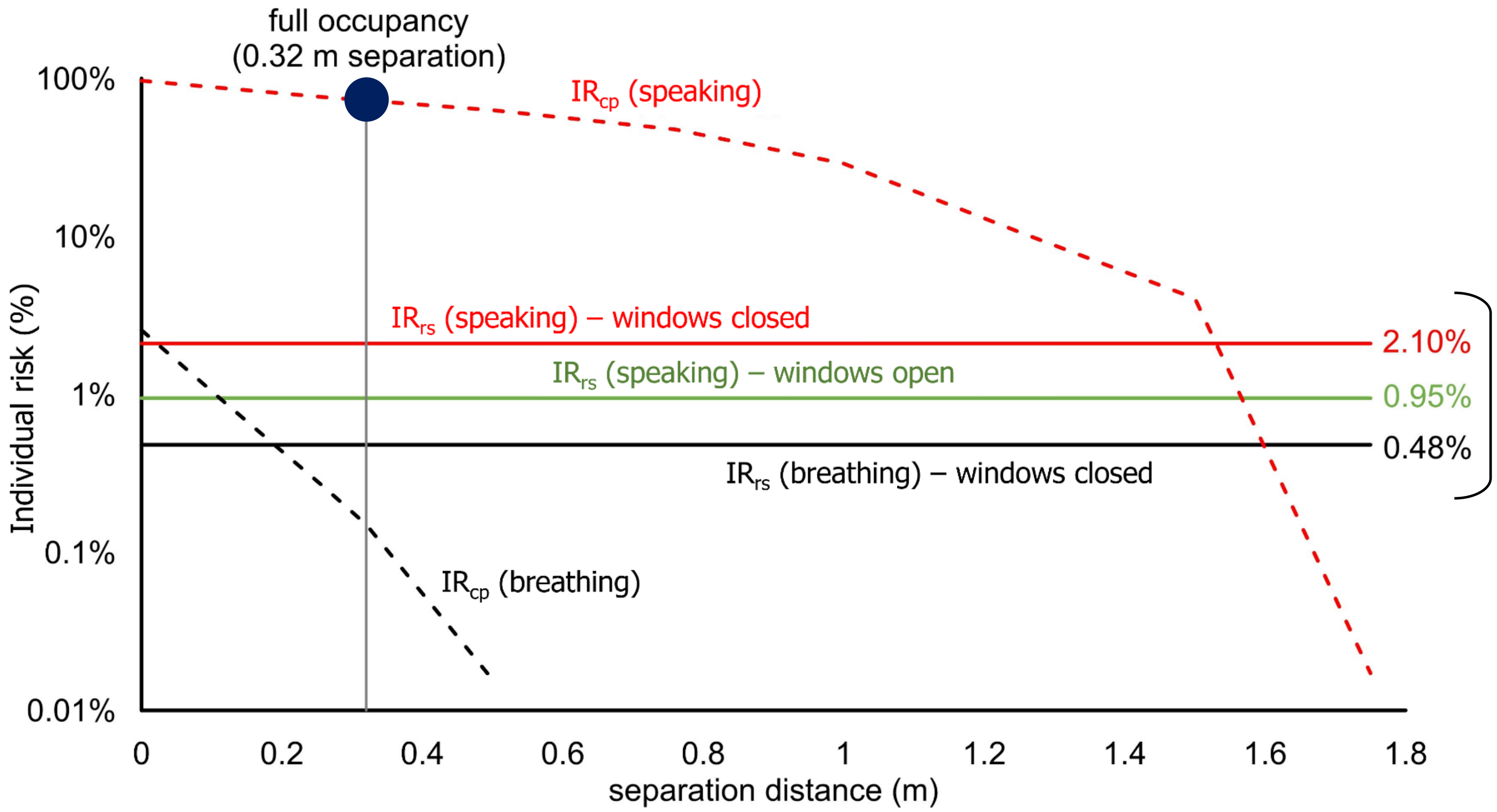
- **urban bus** (average Italian trip: 24-min);
- **long-distance bus** (different travel times)
- different expiratory activities (breathing,
- mitigation strategies (masks, vaccination)
- no filtration of the recirculated air for u ba u
- no filtration, G3 filters and M6 filter for long-dis nce buses (efficiency 0%, 4%, 40%)
- **close proximity risk only for urban buses** (only 1 susceptible person)
- actual (measured) **AERs for urban buses** (CO_2 decay rate approach)

Experiment	AER (h^{-1})
Windows open	65.3 ± 4.6
Windows closed	26.9 ± 3.9

Results: urban buses

Base scenarios: speaking vs. breathing

- contribution of **close proximity** to the individual risk extremely high when the infected subject **speaks** for the entire travel time (up to 75% for full occupancy, i.e. 93 persons, average separation distance 0.32 m);
- negligible

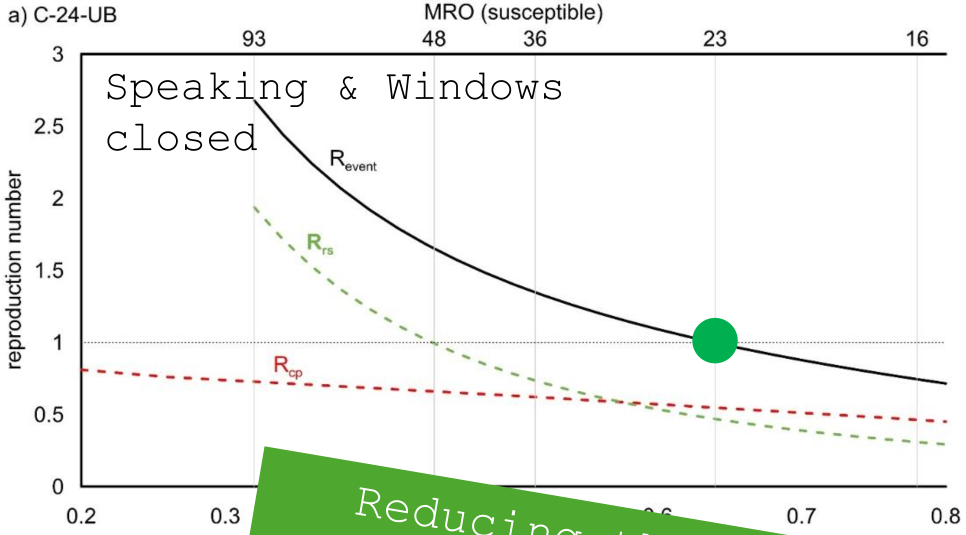


Room-scale risks (well-mixed approach):
No filtration of recirculated air, no masks, no vaccination

Results: urban buses

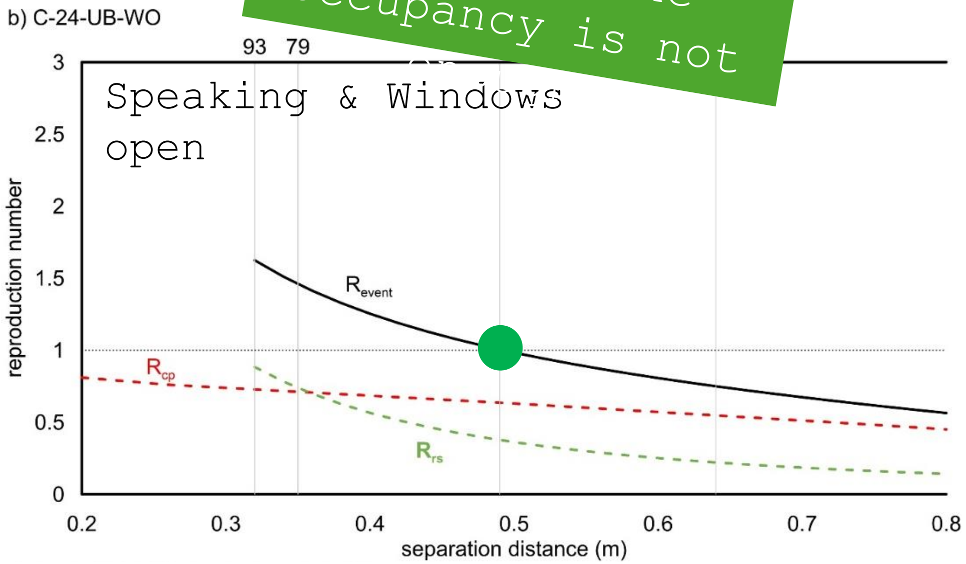
Effect of the ventilation

- R_{event} considering both close proximity (R_{cp}) and room-scale (R_{rs}) contributions
- Equivalent maximum room occupancies (MROs) equal to 23 passengers and 40 passengers for windows closed and opened respectively;
- R_{event} < 1 when FFP2 masks are worn

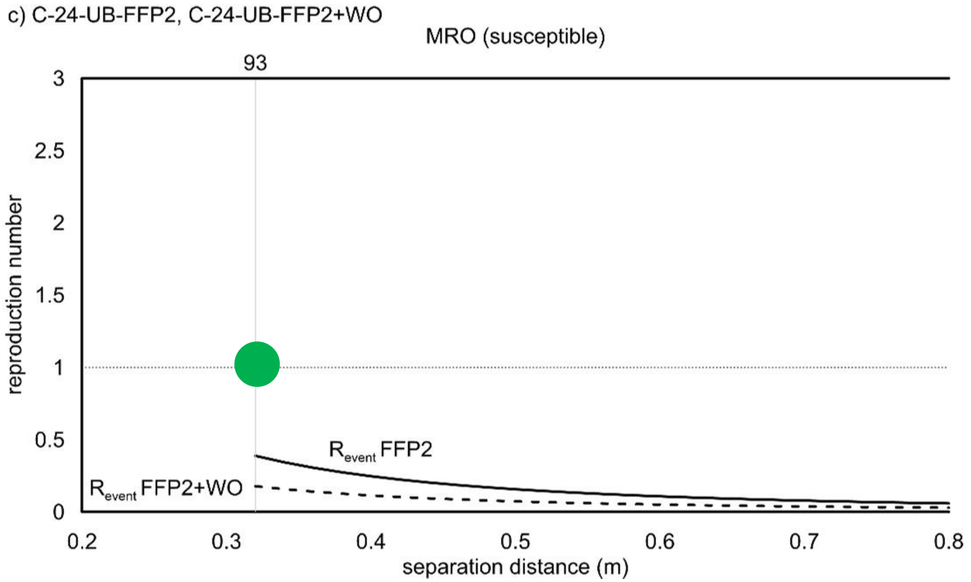


Speaking & Windows closed

Reducing the occupancy is not



Speaking & Windows open

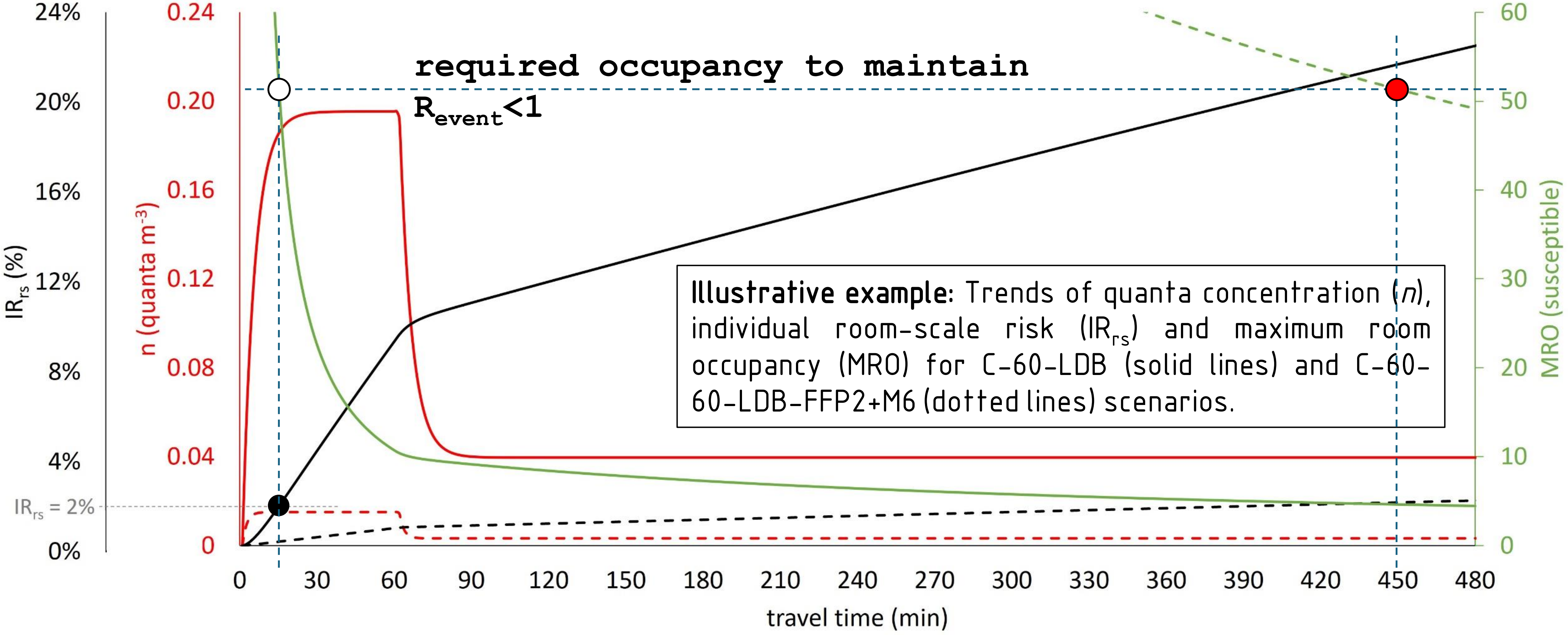


Results: long-distance buses

Travel duration effect, masking effect

- An illustrative example…

(infected commuter speaking for the first minutes (e.g. 60 min) and oral breathing for



required occupancy to maintain R_{event}<1

Illustrative example: Trends of quanta concentration (*n*), individual room-scale risk (IR_{rs}) and maximum room occupancy (MRO) for C-60-LDB (solid lines) and C-60-60-LDB-FFP2+M6 (dotted lines) scenarios.

Results: long-distance buses

Summary of the results

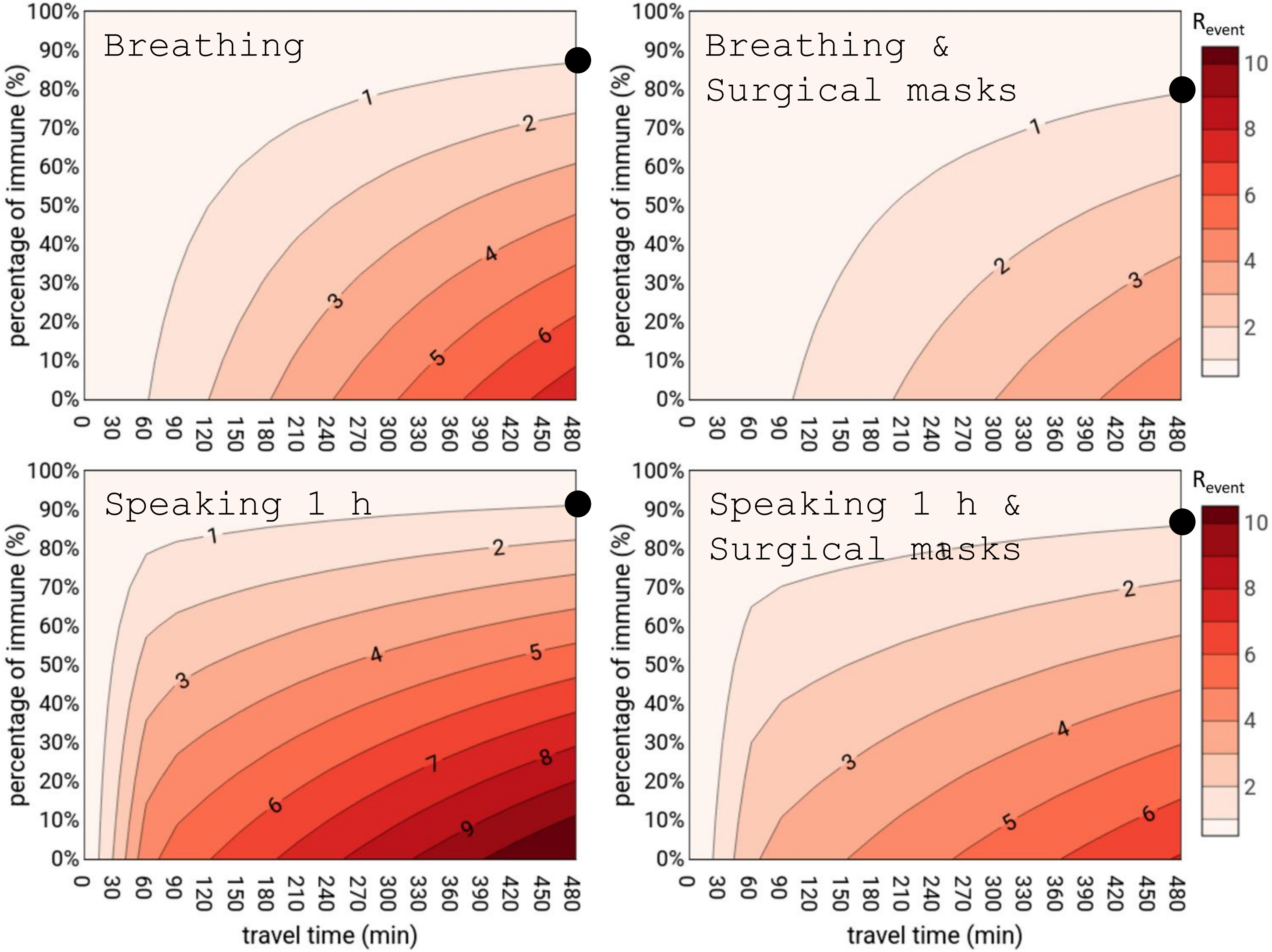
- **required MRO to maintain $R_{event}<1$** for all the investigated scenarios for long-distance buses

Scenarios		Travel time			
		60 min	120 min	240 min	480 min
Base scenario	C-0-LDB	*	25	13	7
Commuter's speaking effect	C-30-LDB	15	12	8	5
	C-60-LDB	11	8	6	4
Filtration G3 & speaking effect	C-60-LDB-G3	12	10	7	5
Surgical mask effect	C-0-LDB-SM	*	42	21	11
Filtration M6 effect	C-0-LDB-M6	*	*	30	15
Filtration M6 & speaking effect	C-60-LDB-M6	26	21	15	10
Surgical mask & speaking effect	C-60-LDB-SM	18	14	10	7
FFP2 & speaking effect	C-60-LDB-FFP2	*	40	30	20
FFP2 & filtration M6 effect	C-60-LDB-FFP2+M6	*	*	*	49

Results: long-distance buses

Immunization effect

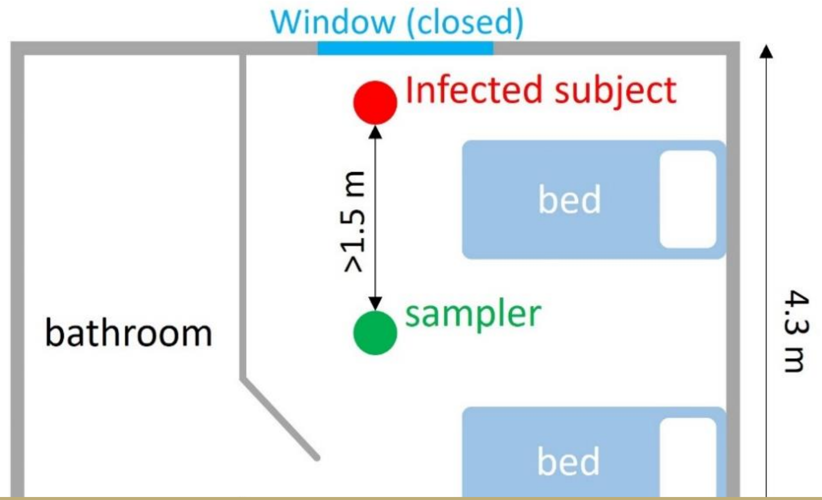
- The presence of the immunes can reduce virus transmission;
- only a percentage of immunes higher than 90% would allow a $R_{event}<1$ in the case of 480-min trips **with no masks**;
- even if **surgical masks** were worn, a high percentage of immunes would still be required, i.e. at least 80% and 85% for oral breathing and speaking activities, respectively.

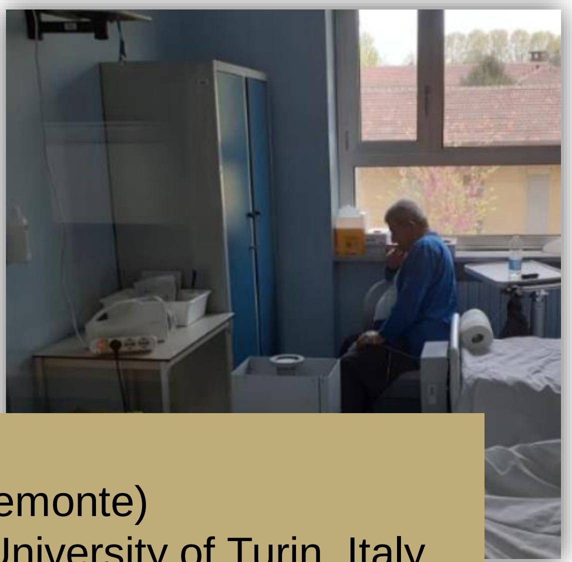


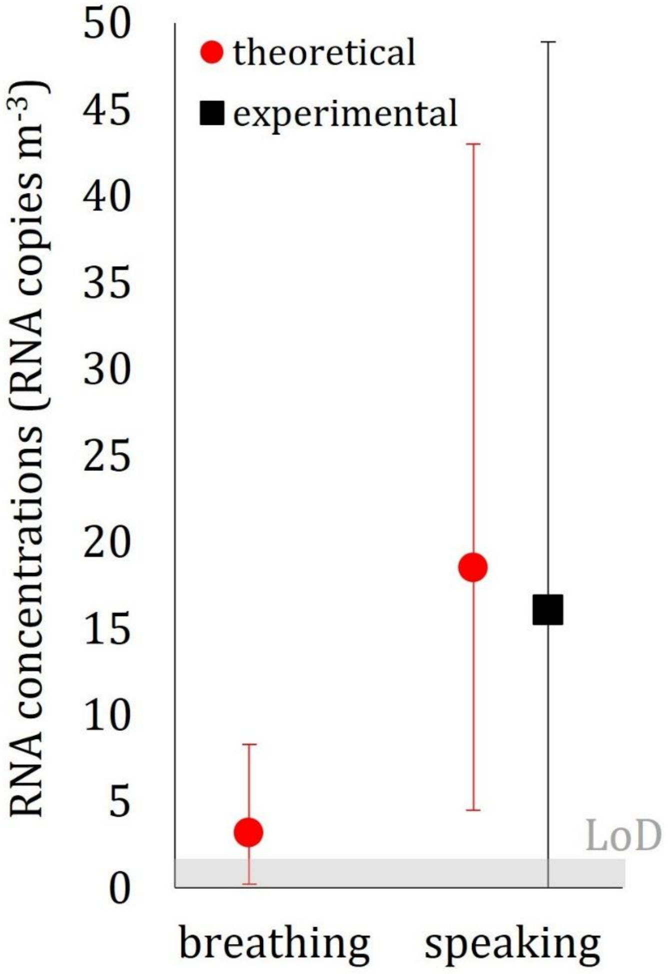
Discussions: can we trust the approach?

Experimental validation of the room-scale approach

- Experimental analysis in controlled conditions (hospit
- Infected subject with a measured viral load (emission)
- Scenarios: speaking & breathing
- Viral load concentration in air: measured vs. predicte







In collaboration with:
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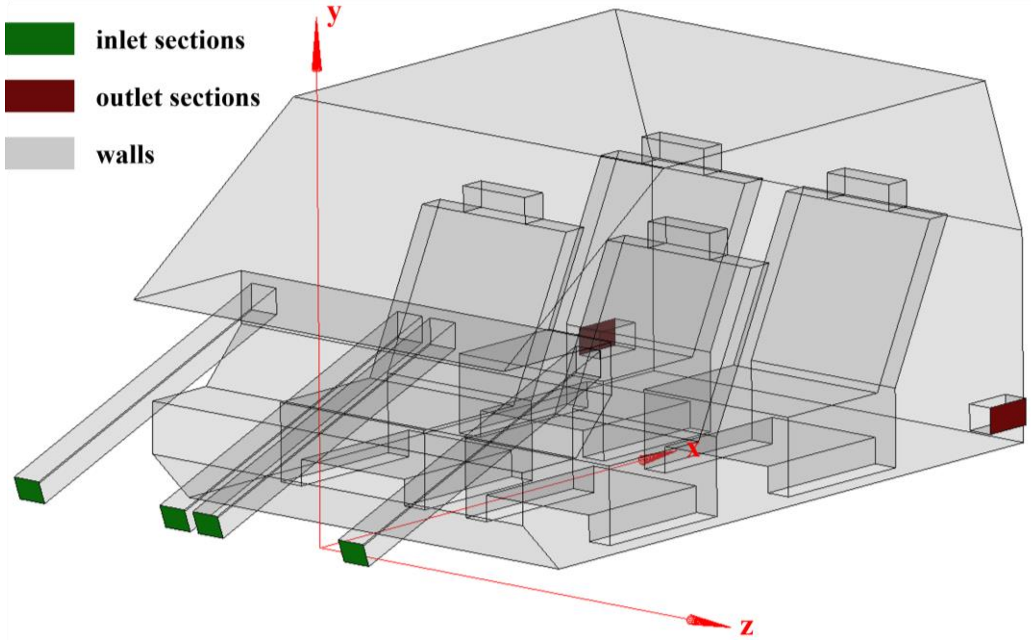
Azienda Ospedaliero-Universitaria San Luigi Gonzaga, University of Turin, Italy
Amedeo di Savoia Hospital, University of Turin, Torino, Italy

Conclusions

- **The risk of infection in transport microenvironments can be predicted!**
- For **urban buses**, the contribution of close proximity to the individual risk is extremely high when the infected subject **speaks** for the entire travel time, thus significantly contributing to the reproductive number and, consequently, to the maximum occupancy of the bus in view of controlling the transmissibility of the pandemic.
- The maximum occupancy to guarantee a $R_{event}<1$ (MRO) would be lower than the full occupancy of the bus both with the windows closed (MRO = 23 commuters) and with windows open (MRO = 40 commuters). To maintain a $R_{event}<1$ for full occupancy of the bus, masks should be adopted.
- For a **breathing** infected subject, the close proximity risk is negligible, and the room-scale contribution is 0.48%, thus guaranteeing a $R_{event}<1$ with full occupancy of the bus.
- For **long-distance buses** (where the close proximity contribution can be reasonably neglected due to the distances and orientation amongst the commuters; thus, the risk is only related to the room-scale contribution) the total exposure (travel) time and the adoption of mitigation solutions significantly affect the MRO.
- Reducing the speaking time and adopting frequent breaks during the trip represent very basic solutions that cannot always be applied. As an example, in the case of an infected person **speaking for 1 h**, only **high quality filtration of the recirculated air** and the simultaneous use of FFP2 masks would permit full occupancy of the bus up to almost 8 h; otherwise, an extremely high percentage of immunized persons (> 80%) would be required.

Experimental validation of the numerical model (scale 1:5)



Arpino, F., Cortellessa, G., Grossi, G., Nagano, H., 2021. ***A Eulerian-Lagrangian approach for the non-isothermal and transient CFD analysis of the aerosol airborne dispersion in a car cabin.*** *Building and Environment 108648. https://doi.org/10.1016/j.buildenv.2021.108648*

Experimental validation of the numerical model (scale 1:5)

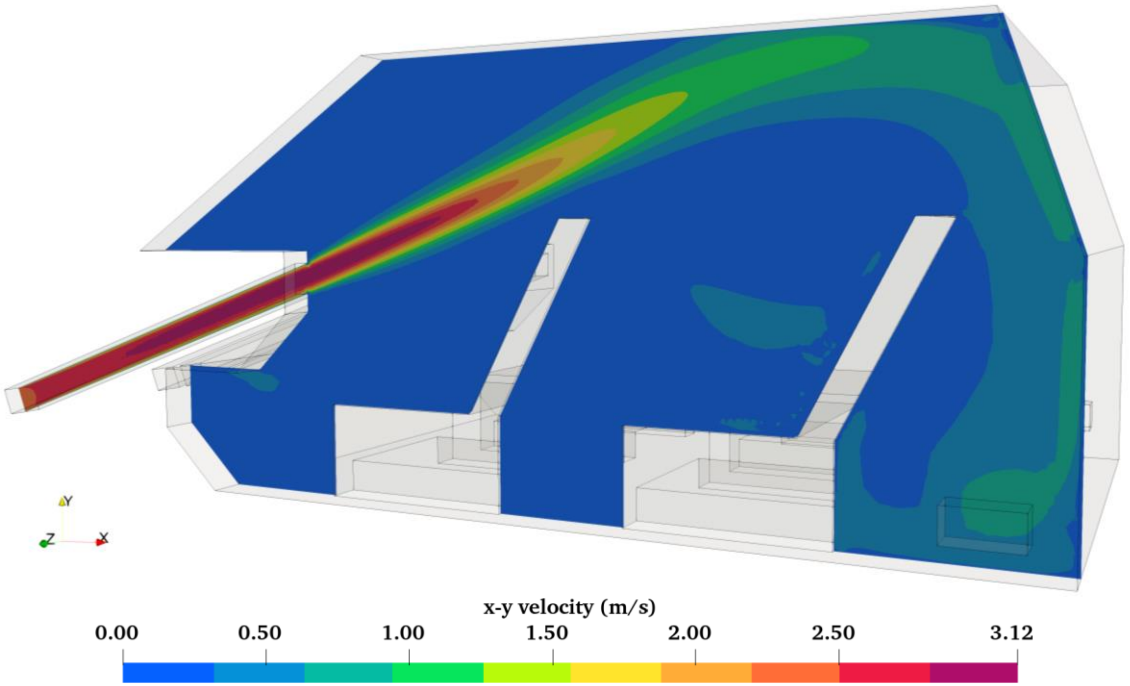


Figure 6 – x-y velocity contours on the slice at z=0.3945 m (measuring plane) with SST *k-ω* turbulence model.

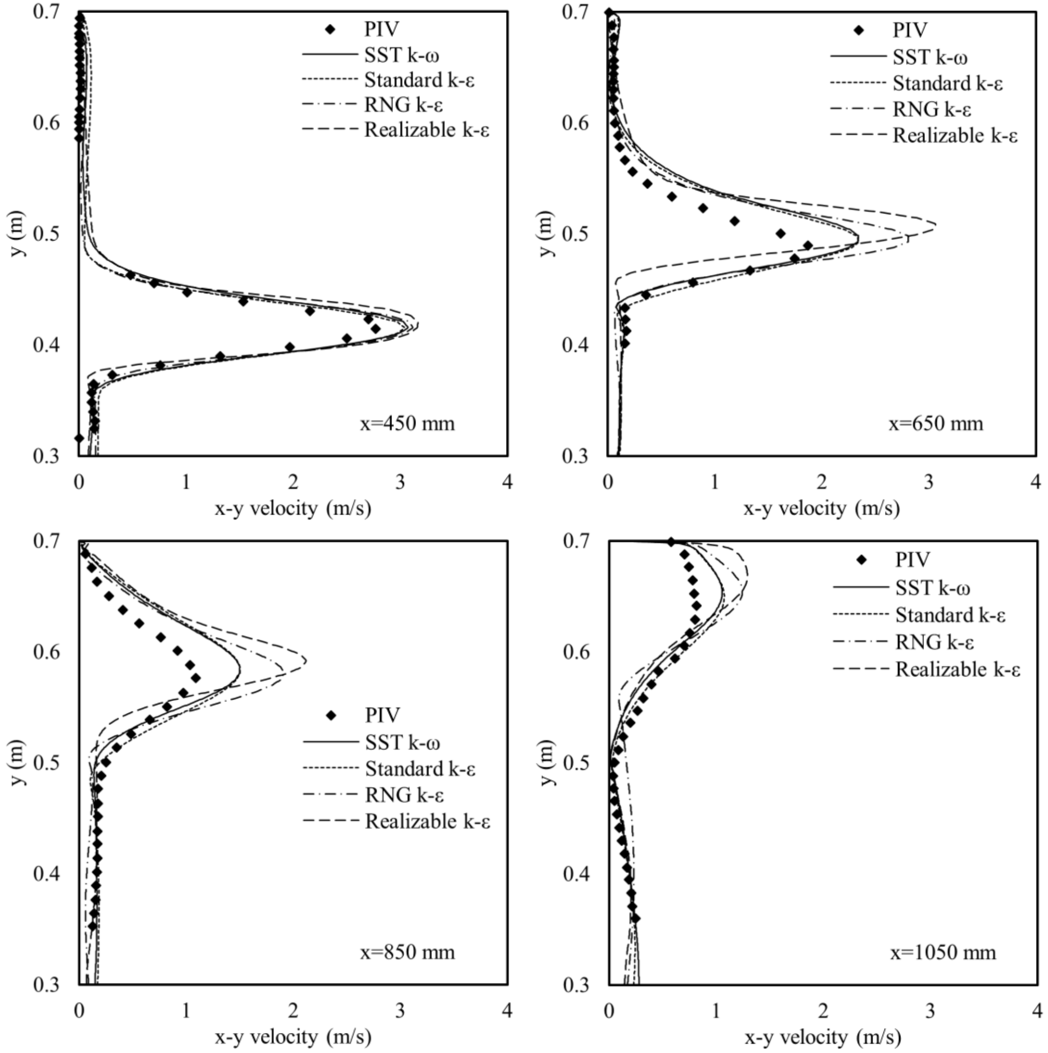
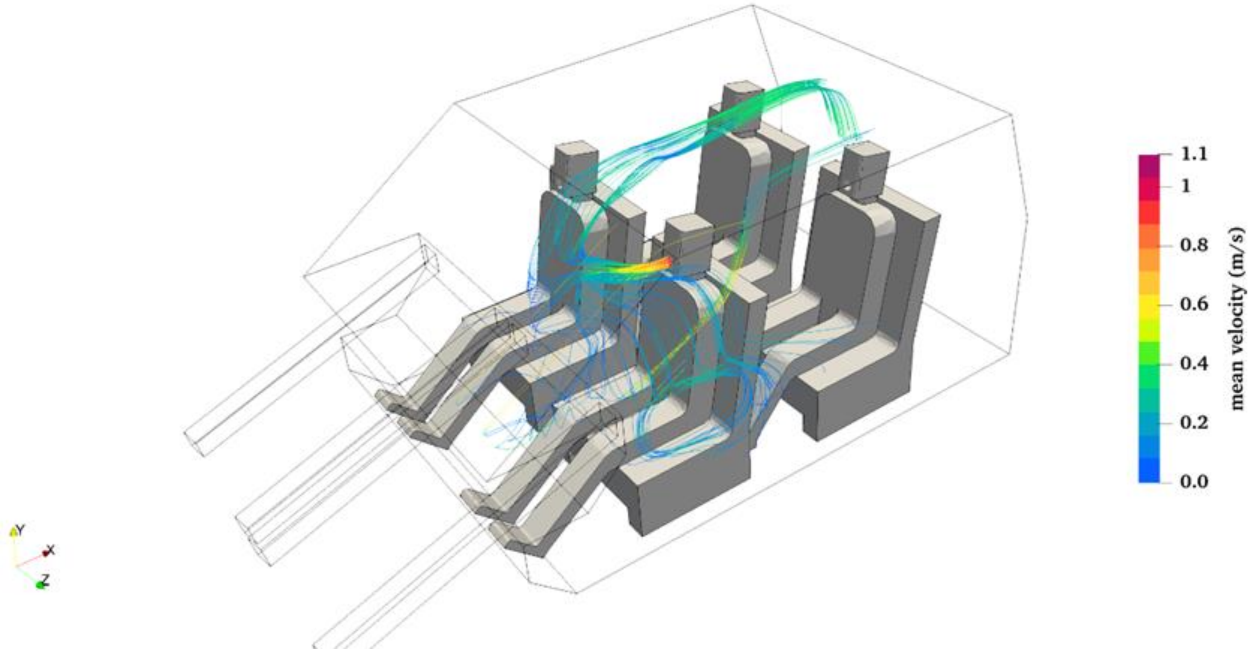


Figure 7 – Experimental and numerical velocity profiles comparison within a selected x-y plane at z=0.3945 m obtained in four different sections: x=0.45 m, x=0.65 m, x=0.85 m and x=1.05 m.

Scenarios investigated (30 min journey)	position of the infected subject	HVAC system flow rate	HVAC ventilation mode	expiratory activity of the infected subject
influence of the position of the infected subject	driver, passenger sitting on the right rear seat (passenger 3)	$Q_{50\%}$	mixed	speaking
influence of the HVAC system flow rate	driver	$Q_{10\%}$, $Q_{25\%}$, $Q_{50\%}$, $Q_{75\%}$, $Q_{100\%}$	mixed	speaking
influence of the HVAC ventilation mode	driver	$Q_{50\%}$	mixed, front, windshield defrosting	speaking

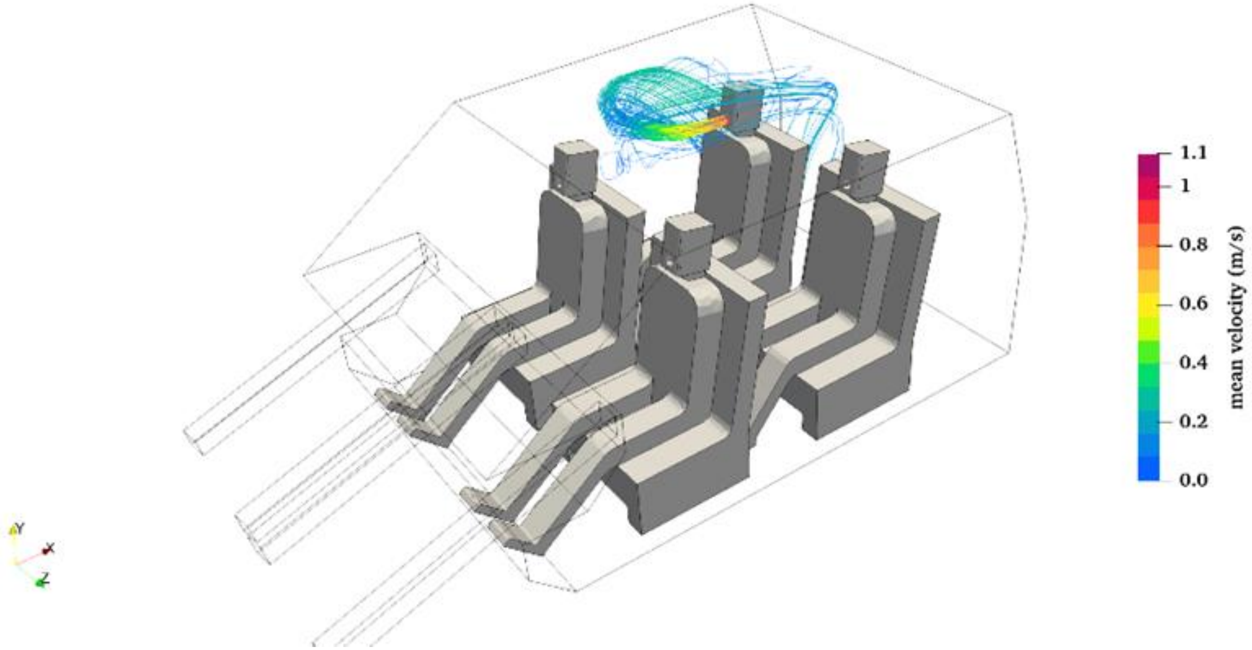
Arpino, F., Grossi, G., Cortellessa, G., Mikszewski, A., Morawska, L., Buonanno, G., Stabile, L. Risk of SARS-CoV-2 in a car cabin assessed through 3D CFD simulations (2022) Indoor Air, 32 (3), art. no. e13012

Influence of the position of the infected subject



Streamlines of the airflows (coloured by velocity) exiting the mouth of the infected driver in case of mixed ventilation mode at 50%

Driver infected			
		Individual infection risk (%)	
Susceptible subject	Inhaled volume (mL)	CFD	Well-mixed
Driver	emitter		
Passenger #1	1.89×10^{-9}	9.2%	42%
Passenger #2	8.68×10^{-9}	26%	
Passenger #3	4.49×10^{-9}	18%	



Streamlines of the airflows (coloured by velocity) exiting the mouth of the infected passenger #3 in case of mixed ventilation mode at 50%

Passenger #3 infected			
		Individual infection risk (%)	
Susceptible subject	Inhaled volume (mL)	CFD	Well-mixed
Driver	5.17×10^{-11}	0.30%	42%
Passenger #1	1.42×10^{-9}	7.2%	
Passenger #2	1.59×10^{-11}	0.09%	
Passenger #3	emitter		

Influence of the HVAC system flow rate

HVAC air flow rate	Inhaled volume (mL)			Individual infection risk (%)			
	Passenger #1	Passenger #2	Passenger #3	Passenger #1	Passenger #2	Passenger #3	
				CFD	CFD	CFD	Well-mixed
$Q_{100\%}$	0	1.32×10^{-10}	5.22×10^{-10}	0	0.76%	2.9%	35%
$Q_{75\%}$	4.59×10^{-12}	7.97×10^{-11}	3.62×10^{-10}	0.03%	0.46%	2.0%	38%
$Q_{50\%}$	1.89×10^{-9}	8.68×10^{-9}	4.49×10^{-9}	9.2%	26%	18%	42%
$Q_{25\%}$	1.87×10^{-8}	1.67×10^{-9}	1.42×10^{-9}	36%	8.3%	7.2%	48%
$Q_{10\%}$	8.30×10^{-8}	1.02×10^{-7}	1.37×10^{-8}	51%	53%	32%	55%