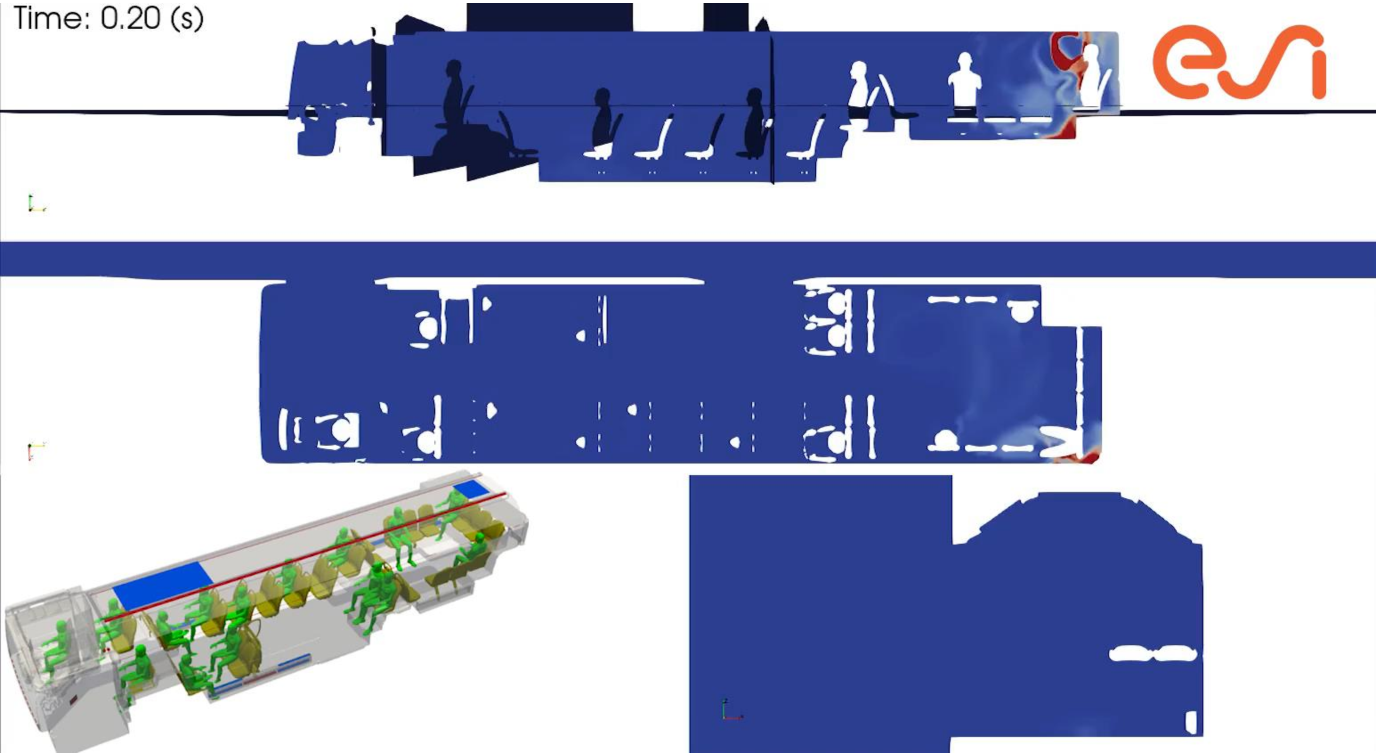
get it right

Simulation of the distribution of aerosols in public transport to determine the infection risk using Model Order Reduction



6th German OpenFoam User MeetiNg

S. Vilfayeau[1], Ruediger Magg[2], A. Rayudu[2], A. Mysore Nanjundaswamy Rao2, Fred Mendonca[3], M. Cameron[4], M. Reiserer[5], N. Schneider[5], C. Sommer[5], A. Berger[1]

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[4]ESI Group, France
[5]Universität Kassel, Germany

20/10/2021

Public

esi-group.com

Annoucement

OpenFOAM and Visual-CFD Highlights Release

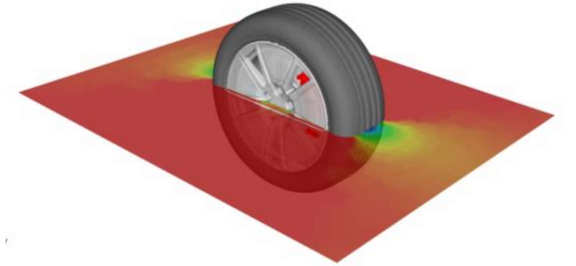
OpenFOAM
Highlight Release (v2106 & v2112)

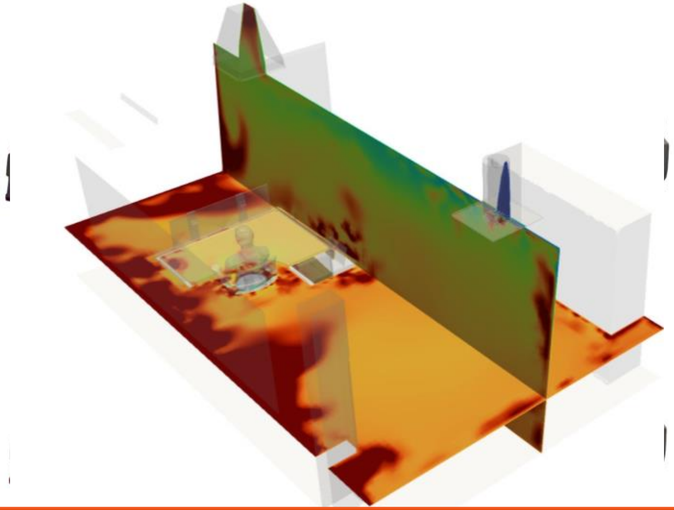
- **AMI Performance Improvement**
  - ***faceAreaWeightAMI2D*** AMI method (weights calculation)
    - 5% speed-up
  - Implicit handling of coupled patches (AMI and inter-region BC for CHT)
    - 10% speed-up

- **New finite area thin film**
  - various improvements to Finite Area library (parallel, pre-, post-)
  - liquid film modelling based on FAM

- **New smoothed surface sensitivity maps**

- **New comfort function object**
  - PPD, PMV, DR compliant with ISO EN 7730:2005





PPD - predicted percentage of dissatisfaction

Visual-CFD: Latest Release

Species transport & Combustion

Species transport & Combustion

- Physical properties of species set
- Reactions
  - Defining rection
  - Importing detailed chemistry reactions
- Chemistry solvers
- Combution models

Visual-CFD: Latest Release
Aero acoustic process

Hybrid Method (incompressible)

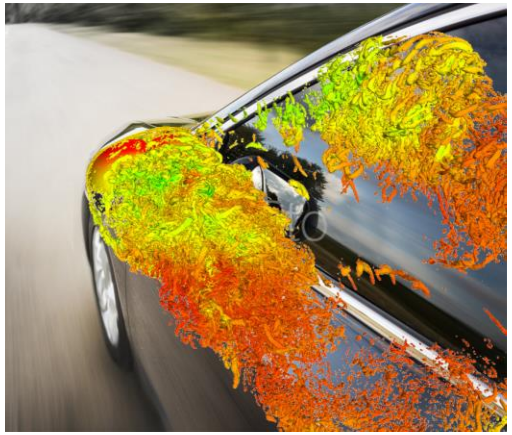
- Hydrodynamic:
  - DES turbulence model
  - DES hybrid convective Scheme
- Acoustic:
  - Curle acoustic analogy

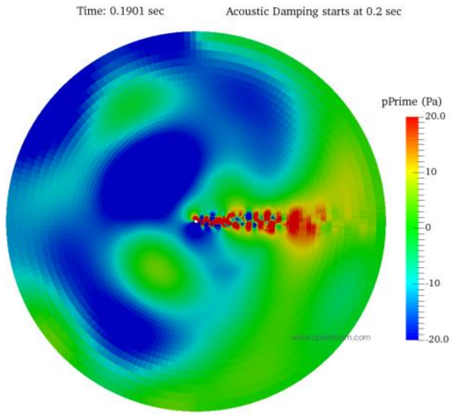
Direct Method (compressible)

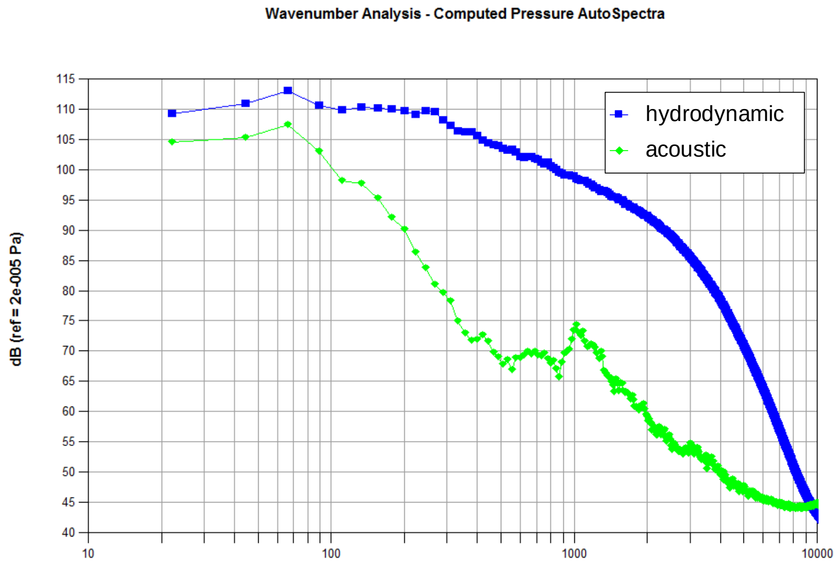
- Hydrodynamic+Acoustic:
  - DES turbulence model
  - DES hybrid convective Scheme
  - Acoustic damping

Pre-/Post-Processing

- Acoustic Power (Proudmann)
- Noise Utility



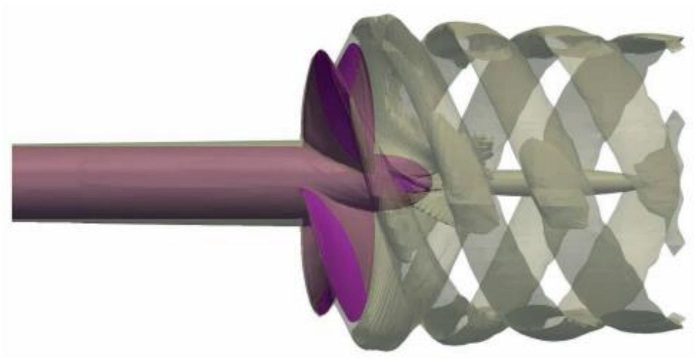


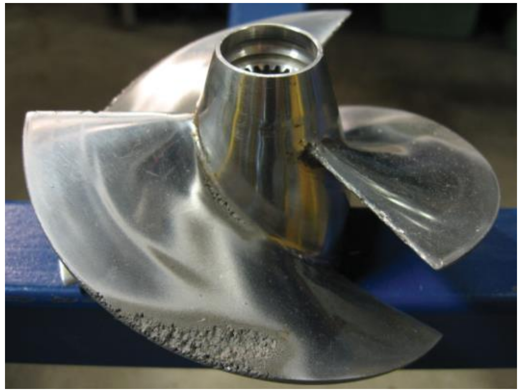


Average fluctuating surface pressure on side glass

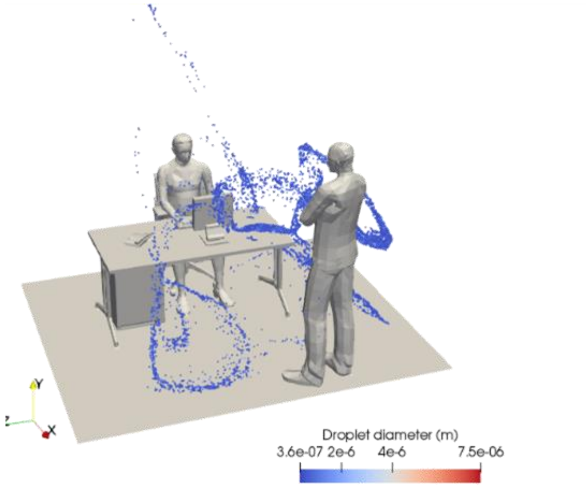
Visual-CFD: Up coming Release (VE 18.0, June 2022)

Cavitation



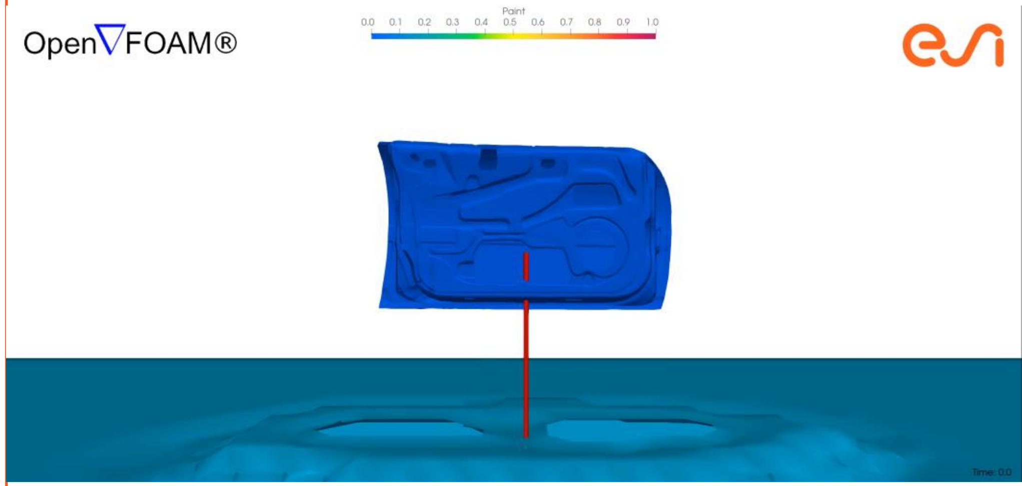


Spray modeling

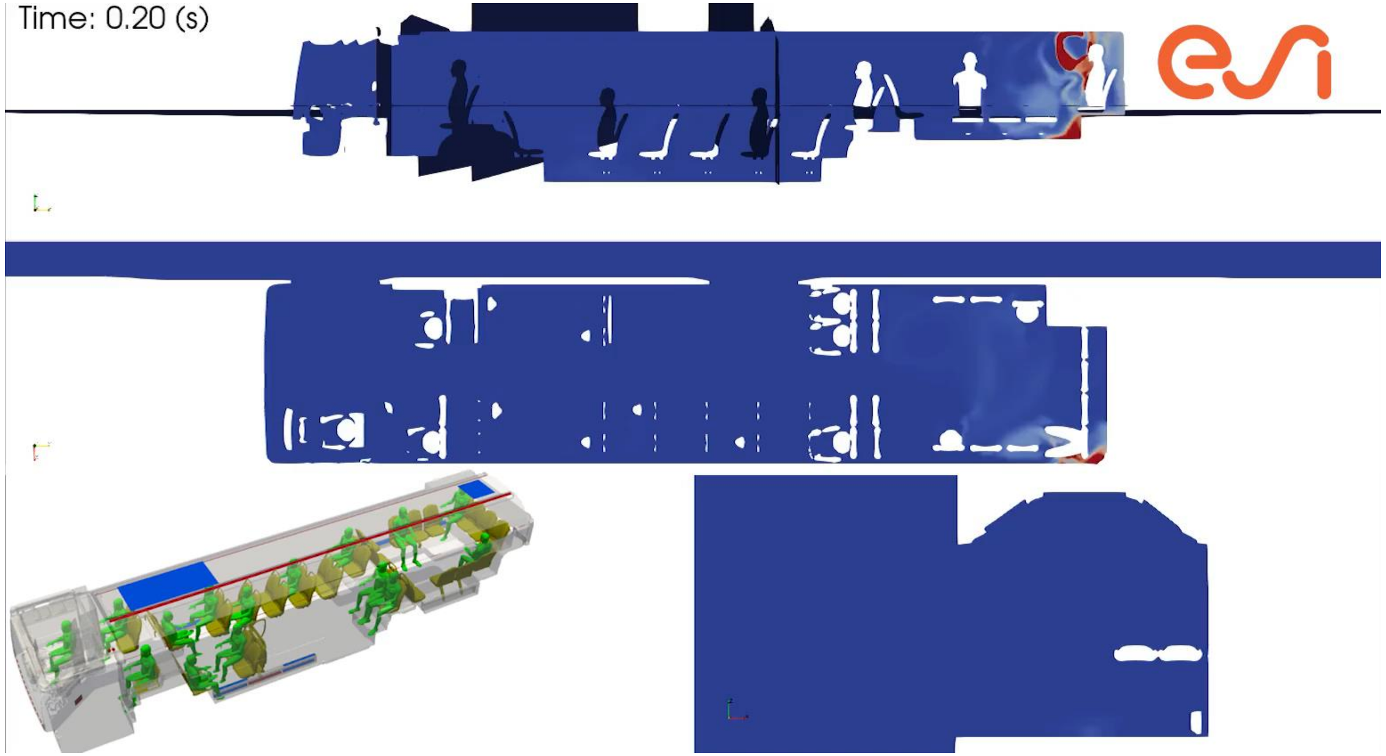


Tutorials

- Thermal Comfort Tutorial
- Paint Dipping Tutorial



Simulation of the distribution of aerosols in public transport to determine the infection risk using Model Order Reduction



Motivation
Problem Situation

- The pandemic has caused more people to be afraid of infection by airborne pathogens
  - aerosols are the main transmission route for SARS-CoV-2 viruses
- People increasingly avoid places where many people meet in confined spaces, such as offices or public transport
  - use of public transport decreased by up to 80% in the meantime
- There is an urgent need to counteract the loss of trust in public transport providing evidence of the effectiveness of measures taken to ensure the safety of passengers

Objectives (EMILIA Project)

Funded by BMVI

Bundesministerium für Verkehr und digitale Infrastruktur

UNIKASSEL VERSITÄT

VERKEHRSPLANUNG UND VERKEHRSSYSTEME
Prof. Dr. Carsten Sommer

- **Towards a pandemic resistant public transportation**
  - Develop effective recommendations for transport companies which help to minimize the health risks associated with public transport
  - Increase customer confidence in public transport
  - Consider implications of a pandemic in the design of public transport
- **Research Questions**
  - Which concepts in vehicle design, planning and operation are most effective towards a pandemic resistant public transportation?
  - Which protection measures to mitigate the risk of infection in public transport vehicles already in place are effective?
  - What other interventions can reduce the risk further and support winning back trust and confidence of passengers?

Content

Subtitle

- Challenges
- Solution Approach
  - Overall Process Overview
  - CFD Methodology (Breathing, Talking, Shouting, Mask)
  - Model Order Reduction Methodology
- Results
  - Case Description: Boundary Conditions/ Scenario/ DoE Parameters
  - CFD Results
  - MOR Results + Data Analytics
- Summary & Outlook

Challenges

Tense atmosphere in closed spaces

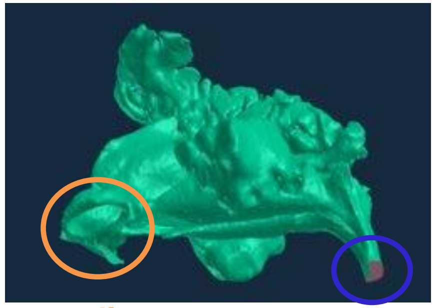
- Breathing is enough to transmit SARS-CoV-2 Virus
- Number of people and extended exposure time increase risk (occupancy level)
- Aerosol distribution depends on people’s behavior and protection measures
  - Breathing, talking, shouting, quality of masks
- Air exchange rate in closed spaces is nonuniform
  - Zonal risk calculators are insufficient => **CFD**

Solution Approach

CFD Methodology: Breathing w/o Mask Scenario

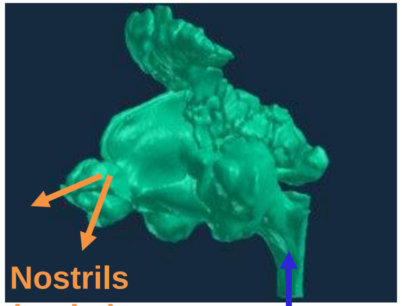
- Nasal geometry created as Pesci 2013 (OpenNOSE: an opensource procedure for the simulation of nasal aerodynamics)
  - Stitched onto face/body mannequin
- Calculate transient breathing cycle (penetration and angle)
- Validation with coughing experiment

Nostril Chamber + Breathing Pattern → CFD Results



Nostrils (outlet)

Throat (inlet)



Nostrils (outlet)

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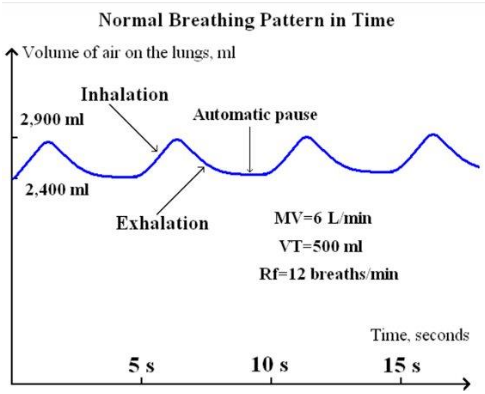
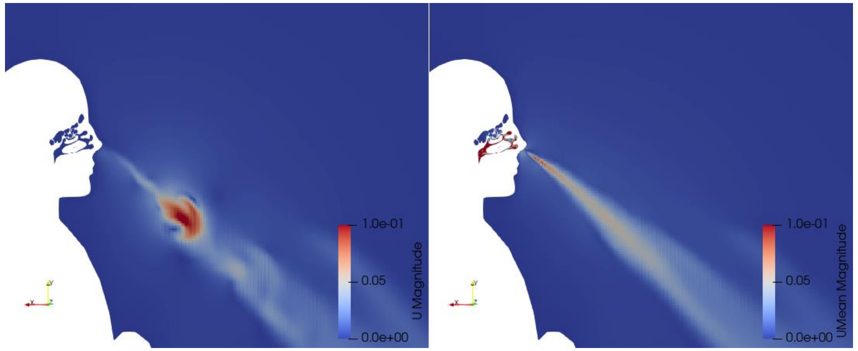


https://www.normalbreathing.com/patterns-normal

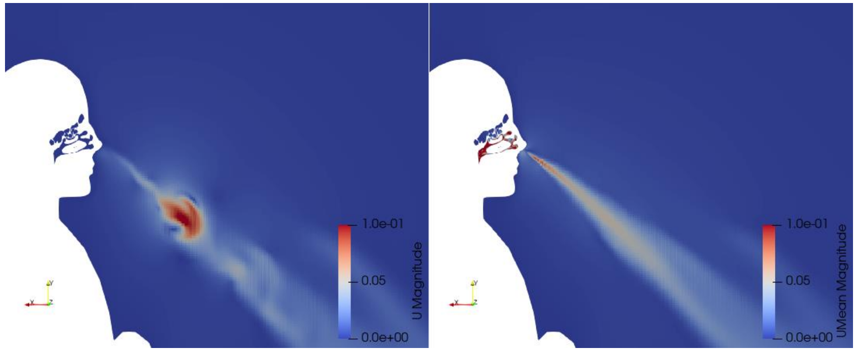


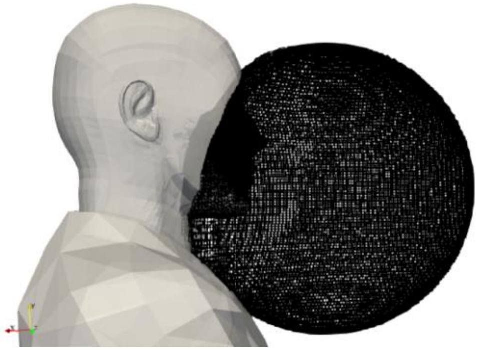
Solution Approach

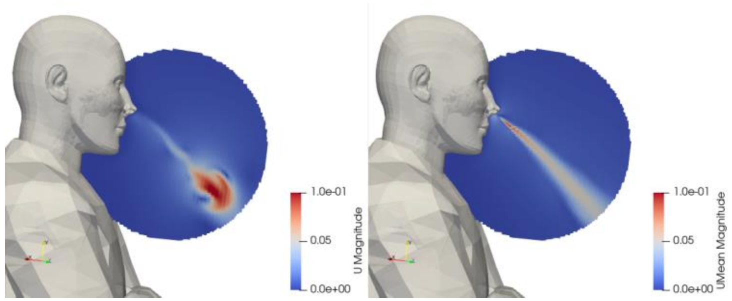
CFD Methodology: Breathing w/o Mask Scenario

- Steady-State Solution initialized with Mapped Transient Mean Data

CFD Results + CellZone → Mapped Transient Mean Data







Solution Approach

CFD Methodology: Talking & Shouting

- Factor 5 from breathing to talking and talking to shouting
  - BUONANNO, G., MORAWSKA, L., et STABILE, L. Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications. Environment international, 2020, vol. 145, p. 106112.

	Breathing (1)	Talking (2)	Shouting (3)
Infected Passenger 1	mapped	0.74988 m^3/h	3.7494 m^3/h
Infected Passenger 2	mapped	0.74988 m^3/h	3.7494 m^3/h
Infected Driver	mapped	0.74988 m^3/h	3.7494 m^3/h

Indoor Air 2010; 20: 31–39
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INDOOR AIR
doi:10.1111/j.1600-0668.2009.00623.x

Characterizing exhaled airflow from breathing and talking

Abstract The exhaled air of infected humans is one of the prime sources of contagious viruses. The exhaled air comes from respiratory events such as the coughing, sneezing, breathing and talking. Accurate information on the thermo-fluid characteristics of the exhaled airflow can be important for prediction of infectious disease transmission. The present study developed a source model to provide the thermo-fluid conditions of the exhaled air from the breathing and talking processes. The source model is a set of equations obtained from the measurements of the flow rate, flow direction, and area of mouth/nose opening with human subjects. It was found that the exhaled flow rate over time can be represented as a sinusoidal function for breathing and a constant for talking. The flow rates can be calculated by physiological parameters of a subject. The direction of the exhalation jet did not vary much between subjects and the area of mouth/nose opening could be regarded as a constant. Though the mouth/nose opening size varied among subjects, they were not correlated with the physiological parameters of the subjects. If combined with appropriate virus and droplet distribution information, the model can be used to describe the disease source due to breathing and talking.

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Key words: Source model; Airborne infection; Airflow; Visualization; Opening area.

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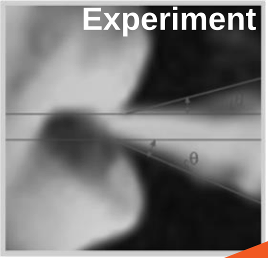


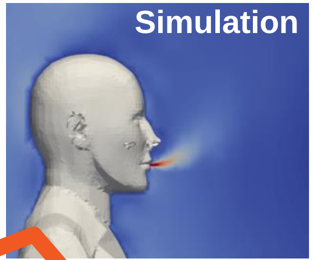
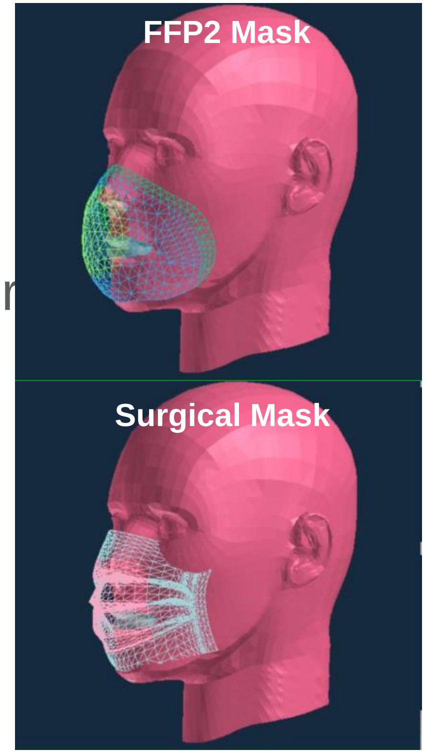


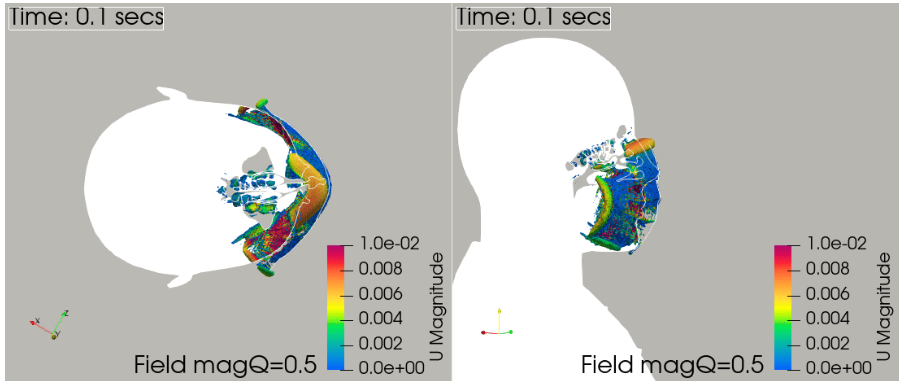
Illustration of the flow field for the talking and shouting scenario.

Solution Approach

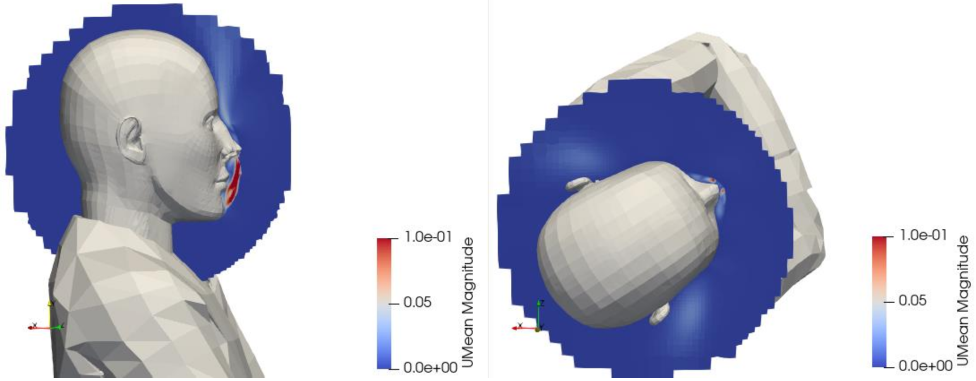
CFD Methodology: Breathing with Mask Scenario

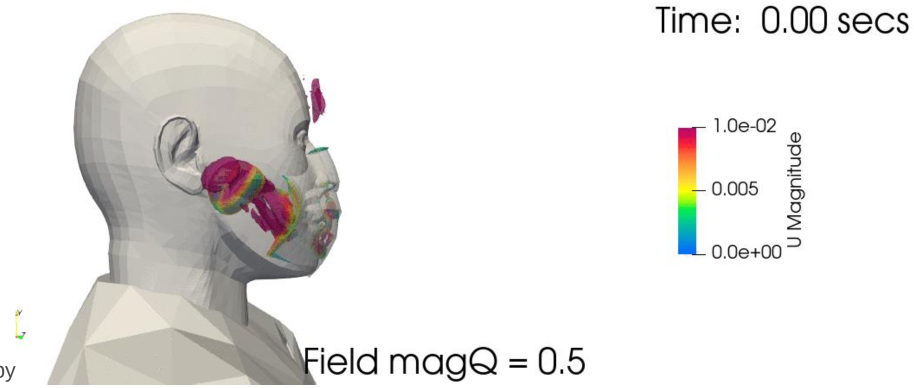
- Variable mask types (FFP2, Surgical) and porosity baffle
  - Porosity coefficient from DBOUK, Talib et DRIKAKIS, Dimitris. On respiratory dr masks. Physics of Fluids, 2020, vol. 32, no 6, p. 063303.

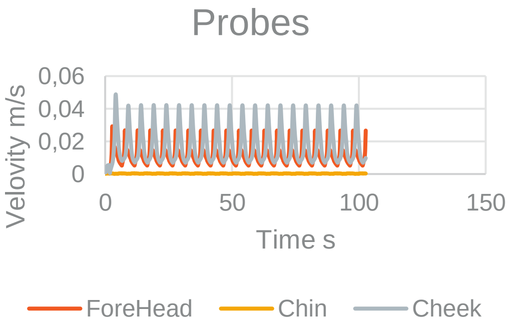




Surgical Mask Mean Velocity Sphere







Solution Approach

CFD Methodology: Correlating CO_2 levels predicted vs measured

- Multiple-occupancy large office

Solution Approach

CFD Methodology: Reciprocity Matrix

- To Determine the infection between passengers and viral load based on scalarTransportFoam with convection and diffusion term
  - One passive scalar per passenger solver on frozen flow
- Output:
  - Square Matrix / Dimension: number of passengers (occupancy)
  - Normalized Scalar

Each column signifies percentage contribution to other element of matrix distribution

Index	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	-1,00E+00	3,41E-10	5,11E-12	1,03E-12	1,70E-15	1,81E-17	2,83E-04	1,69E-12	2,98E-13	5,29E-14	2,13E-17	2,37E-18	4,58E-15	2,52E-16	4,81E-17	9,31E-19	1,97E-19	1,22E-18	2,03E-15	1,05E-16	6,17E-17
1	1,20E-04	-1,00E+00	8,18E-10	9,64E-11	2,27E-13	1,05E-14	1,32E-07	2,46E-04	2,78E-11	5,22E-12	9,06E-15	1,47E-15	5,49E-13	3,06E-14	9,24E-15	1,79E-16	7,35E-17	7,91E-16	2,53E-13	1,89E-14	1,25E-14
2	1,23E-09	1,19E-05	-1,00E+00	5,04E-10	4,11E-13	2,04E-14	7,89E-11	2,37E-09	1,46E-04	9,50E-12	1,75E-14	2,86E-15	9,54E-13	5,34E-14	1,61E-14	3,13E-16	1,39E-16	1,54E-15	4,37E-13	3,28E-14	2,20E-14
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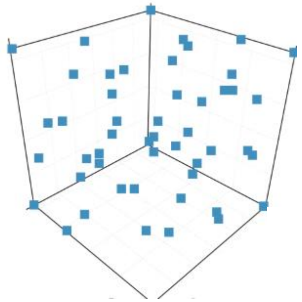
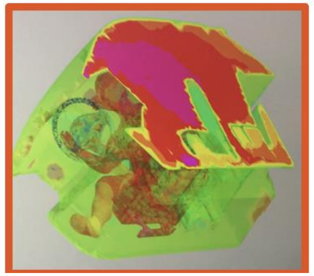
Solution Approach

Model Order Reduction Process

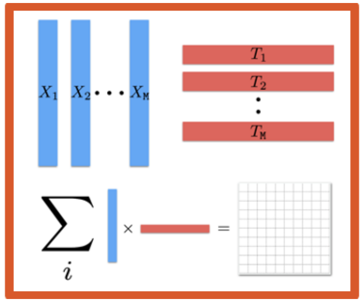
DoE (Sparse/Anova, Multi-dimensional)



Run with the High-Fidelity solver (CFD)



Solution Compression (Reduce Base)

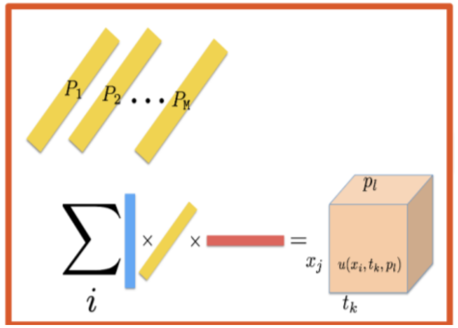


Reduced base in space

Reduced base in time

- Proper ***Orthogonal*** Decomposition (POD)
- Proper ***Generalised*** Decomposition (PGD)
  - ssl-PGD, sPGD, s2PGD, AnovaPGD,

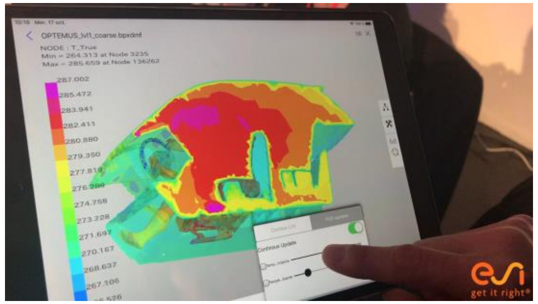
Particularisation of the parametric solution



Reduced base in space

Reduced base in time

Variable



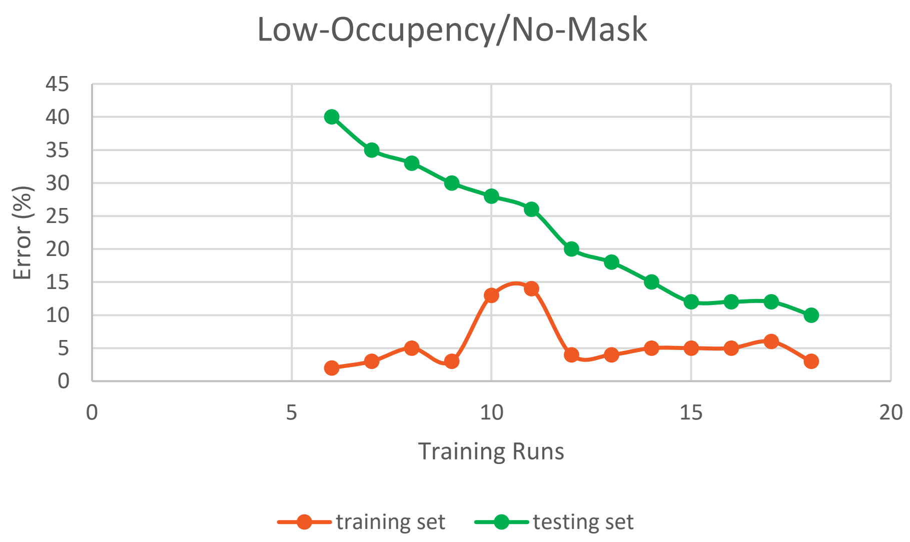
Uniqueness of ESI MOR technology:

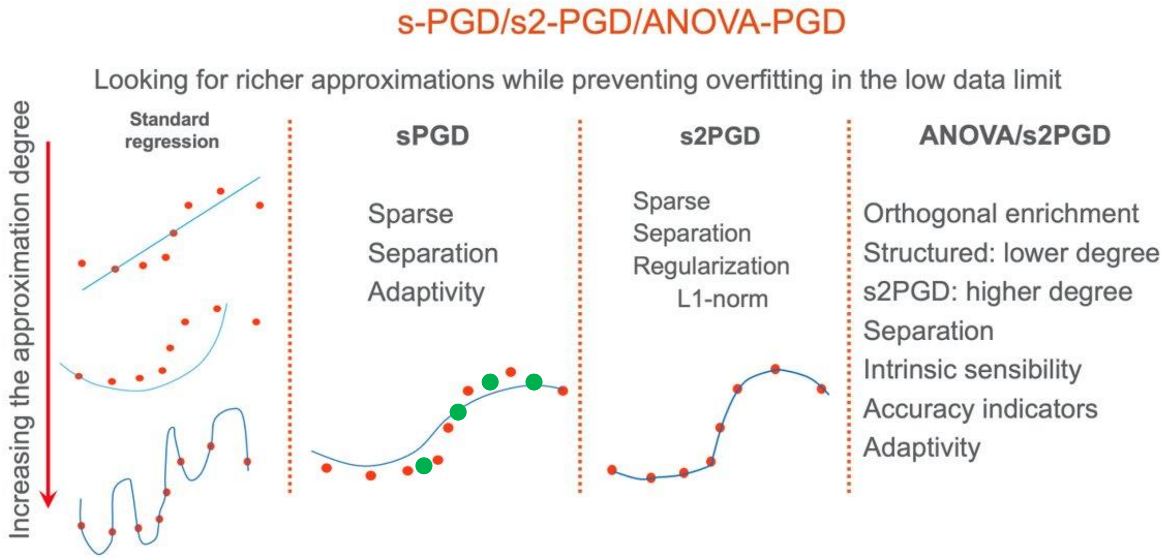
- #cases ~ #parameters
  - Enrichment possible
- Unrestricted distribution DOE cases
- Accuracy above other solutions

MOR Results

Validation

- anovaPGD is applied on the reciprocity Matrix
  - Check error on training set
  - Check error on testing set
    - 15 runs => 10% error





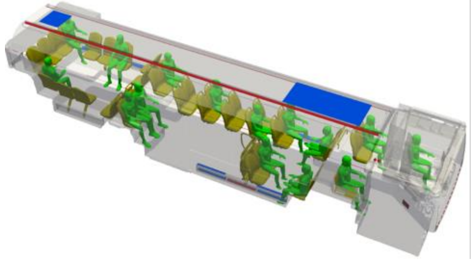
Anova sampling reduces error in the design space extremum

ESI Tool Chaining

CFD Process

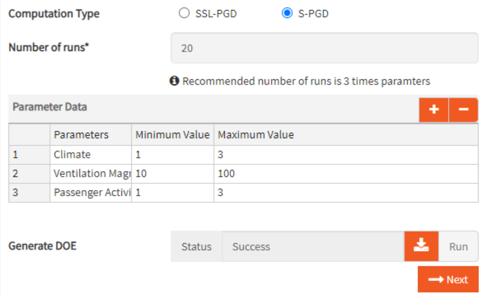
CAD Import

- Environment file (vehicle, seats, inlet, outlet) in stl format
- Occupants file (passengers, mouth, nostril, masks) in stl format



DoE Plan

- Select DoE Method (SSL-PGD, sPGD)
- Select # of training runs
- Specify min/max for each parameter

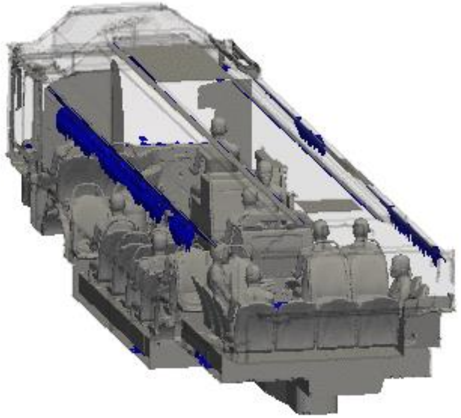


Boundary Conditions

- Inlet Mass Flow Rate & temperature
- Outside temperature
- Wall heat capacity
- Passenger heat flux
- Passenger activities (breathing, talking, shouting)

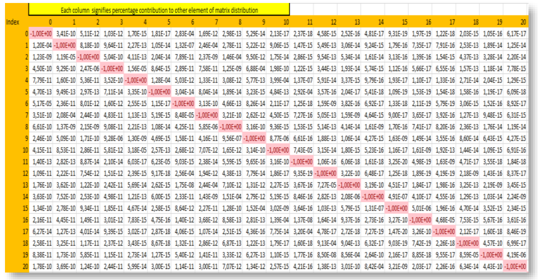
Simulation

- Step 1: meshing
- Step 2: simulation
- Step 3: passive scalar



Post-processing

- Report (Residuals, Volume Average of Age of Air, animation (Iso surface of AoA, Fresh Air Index)
- Reciprocity Matrix in csv format



ESI Tool Chaining

MOR/Data Analytics Process

Data Import

- Import the DoE Plan
- Import the reciprocity matrix for each training runs (.csv format)

AdMOR

- Run the PGD solver
  - Output epgd file

Data Extraction

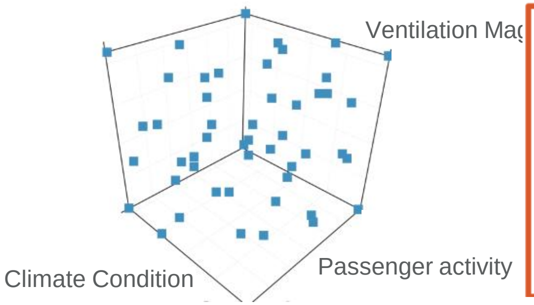
- Import epgd file
- Run Script to extract results for the parametric space

Data Import

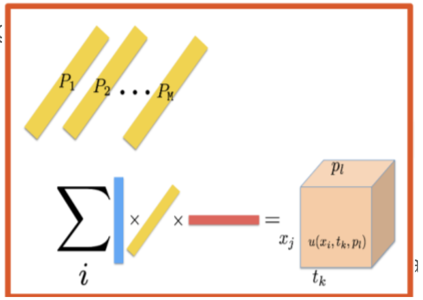
- Import consolidated Results in DataLab (.csv)

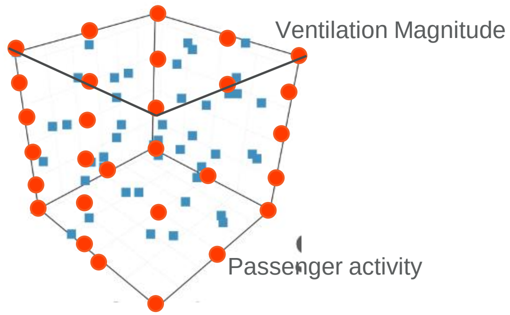
Data Analysis

- Analyze data in data lab

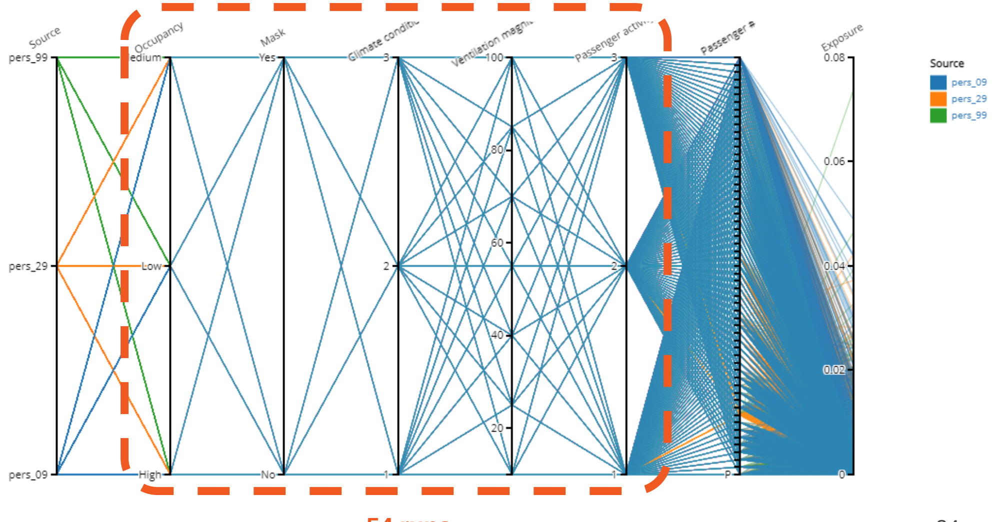


15 training runs





54 runs

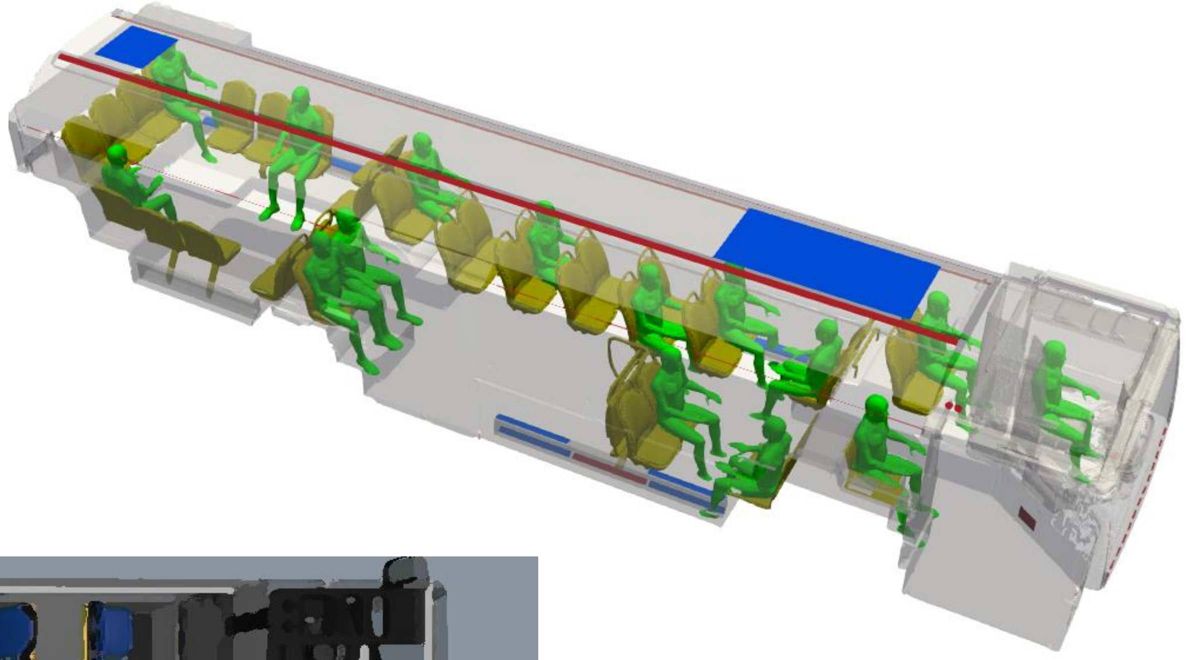


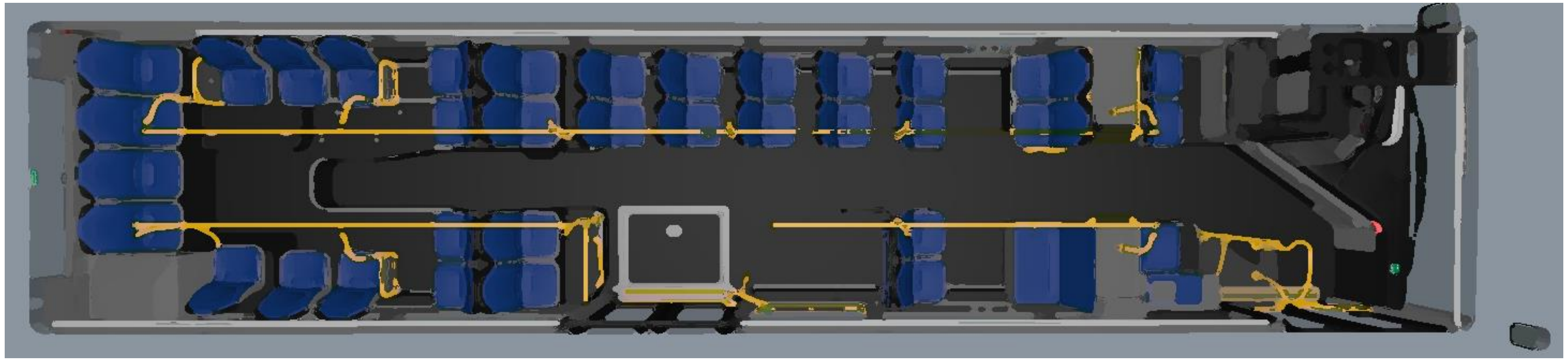
54 runs

CFD Results

Case Description: Geometry

- Vehicle Type 01: Bus
- Maximum Capacity:
  - 36 passengers seated
  - 34 passengers standing (0.25 m2/person)



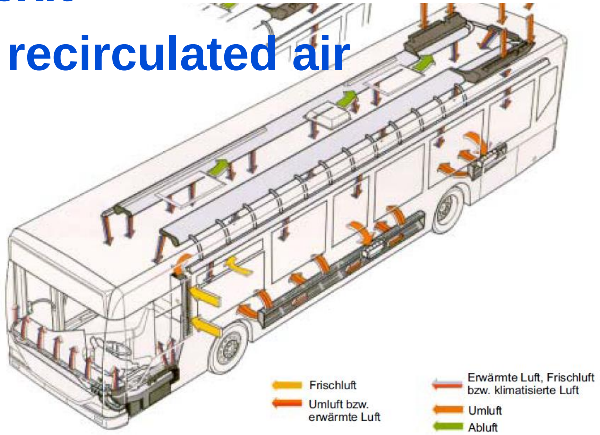


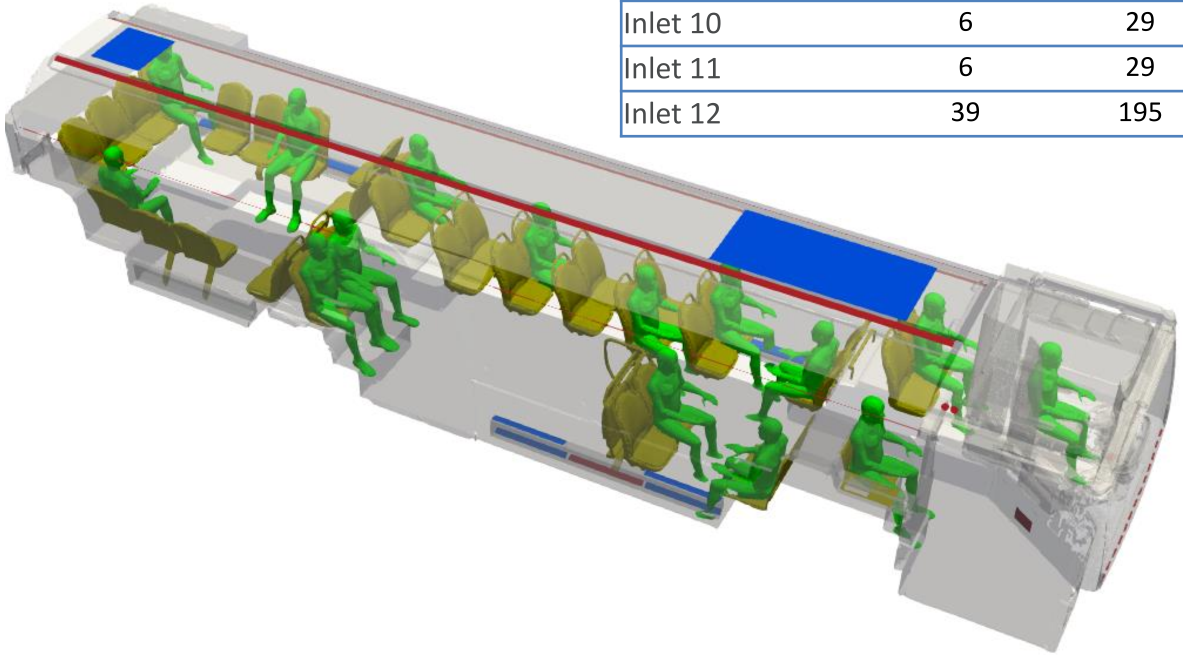
CFD Results

Case Description: Flow Boundary Conditions

- **12 inlets:**
  - **Ceiling: inlet along the bus length (1-4)**
  - **Front door: “air curtain” (5-6)**
  - **Driver (7-9+11)**
  - **Front windshield (10)**
  - **Radiators (1) – only cold scenario**
- **2 outlets:**
  - **Rear outlet: exit**
  - **Front outlet: recirculated air**

Flow rate (m3/h)	10%	50%	100%
Inlet 1	48	240	480
Inlet 2	32	160	320
Inlet 3	32	160	320
Inlet 4	48	240	480
Inlet 5	6	29	57
Inlet 6	6	29	57
Inlet 7	6	29	57
Inlet 8	6	29	57
Inlet 9	6	29	57
Inlet 10	6	29	57
Inlet 11	6	29	57
Inlet 12	39	195	390



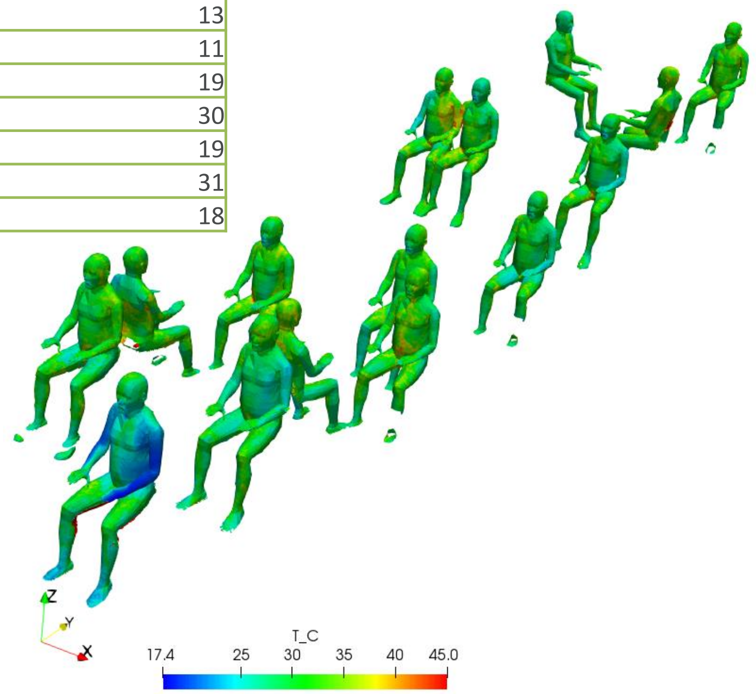


CFD Results

Case Description: Thermal Boundary Conditions

Category	Min Value	Medium Value	Max Value
	Cold (1)	Neutral (2)	Hot (3)
Outside temperature	1.8° C	18° C	27° C
Inside temperature (target)	18° C	18° C	24° C
Inflow air temperature (All inlets)	25,50° C	15° C	19° C
Fresh air ratio	50%	100%	50%
Extra heaters temperature	25,50° C	adiabatic	adiabatic
Extra heaters flow rate (recirculation)	390 m3/h	0 m3/h	0 m3/h
Floor covers engine area only	adiabatic	adiabatic	adiabatic
Remaining floor covers, interior (seats, etc.)	adiabatic	adiabatic	adiabatic
Heat flux of passengers	69 W/m2	69 W/m2	69 (W/m2)
Heat transfer coefficient (walls, ceiling)	12 W/m2-K	12 W/m2-K	12 W/m2-K

Ambient Temperature	**24 °C**	
Air velocity	**0,25 m/s**	
Clothing	**T-shirt, Short, Thongs_sandals**	
HM50EU-SECTOR	**Convection (W/m2)**	**Radiation (W/m2)**
Head face	57	52
Head Hair	63	46
Forehead	62	63
Neck	57	43
Chest	32	13
Back	32	11
Arms	42	19
Hands	89	30
Pelvis	30	19
Legs	51	31
Feet	26	18



CFD Results

Case Description: Simulation Cases – Overview

- **Current MOR solver runs on same mesh**
  - 1 DoE per occupancy level and Mask Quality
  - DoE parameter: climate condition, ventilation magnitude, infected Passenger’s activity
- **Assumptions:**
  - Influence infected passenger’s activities on entire flow field & aerosol distribution is negligible
  - Different mask types per infected passengers will not influence entire flow field significantly

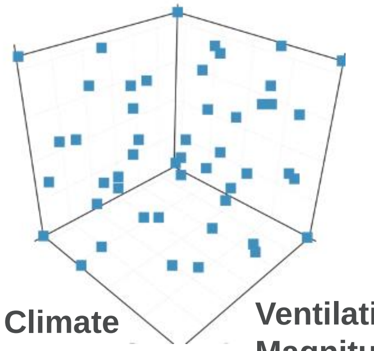
Vehicle Type	Vehicle A					
Scenarios:						
Occupancy Level	High 		Medium 		Low 	
Position Infected Person	Position **1-3**		Position **1-3**		Position **1-3**	
Mask quality	No mask	Pre-defined mask	No mask	Pre-defined mask	No mask	Pre-defined mask
Parameters for DoE:						
Climate Condition	Cold, neutral, hot	Cold, neutral, hot	Cold, neutral, hot	Cold, neutral, hot	Cold, neutral, hot	Cold, neutral, hot
Ventilation magnitude	10-100%	10-100%	10-100%	10-100%	10-100%	10-100%
Infected Passenger's activitiy	Breathing, talking, shouting	Breathing, talking, shouting	Breathing, talking, shouting	Breathing, talking, shouting	Breathing, talking, shouting	Breathing, talking, shouting

CFD Results

Design of Experiment (DoE)

- AnovaPGD: 5 runs per parameters
- Parameters: Climate Condition/ Ventilation Magnitude/ Infected Passenger

RUN_NAME	Climate	Ventilation Magnitude	Infected Passenger Activity	Reciprocity Matrix Name
Run_1	2	55	2	Run_1.csv
Run_2	1	55	2	Run_2.csv
Run_3	3	55	2	Run_3.csv
Run_4	2	10	2	Run_4.csv
Run_5	2	100	2	Run_5.csv
Run_6	2	55	1	Run_6.csv
Run_7	2	55	3	Run_7.csv
Run_8	1	10	1	Run_8.csv
Run_9	1	10	3	Run_9.csv
Run_10	1	100	1	Run_10.csv
Run_11	1	100	3	Run_11.csv
Run_12	3	10	1	Run_12.csv
Run_13	3	10	3	Run_13.csv
Run_14	3	100	1	Run_14.csv
Run_15	3	100	3	Run_15.csv



Climate 1: cold(winter) 2: Neutral: 3: hot(summer)
Infected Passenger Activity 1: breathing 2: speaking 3: shouting

Anova sampling reduces error in the design space extremum

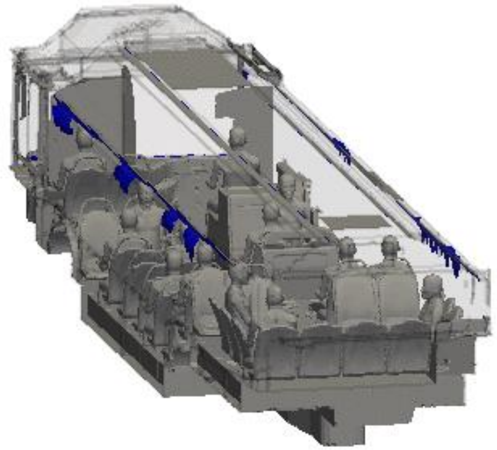
CFD Results

low-occupancy / no-mask (DoE 01)

Run 03 (hot/55%/speaking)

Iso Surface of Age of Air at 1 secs

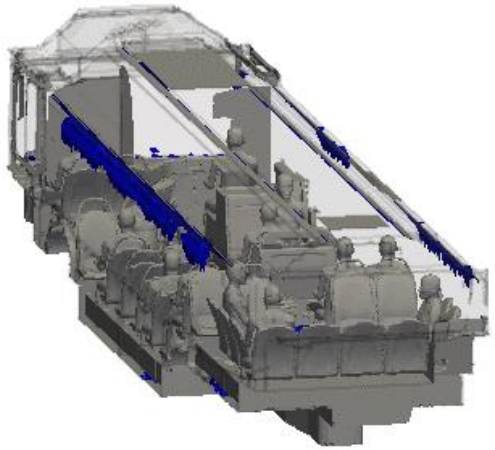
Volume Average of Age of Air: 170 s



Run 10 (cold/100%/breathing)

Iso Surface of Age of Air at 1 secs

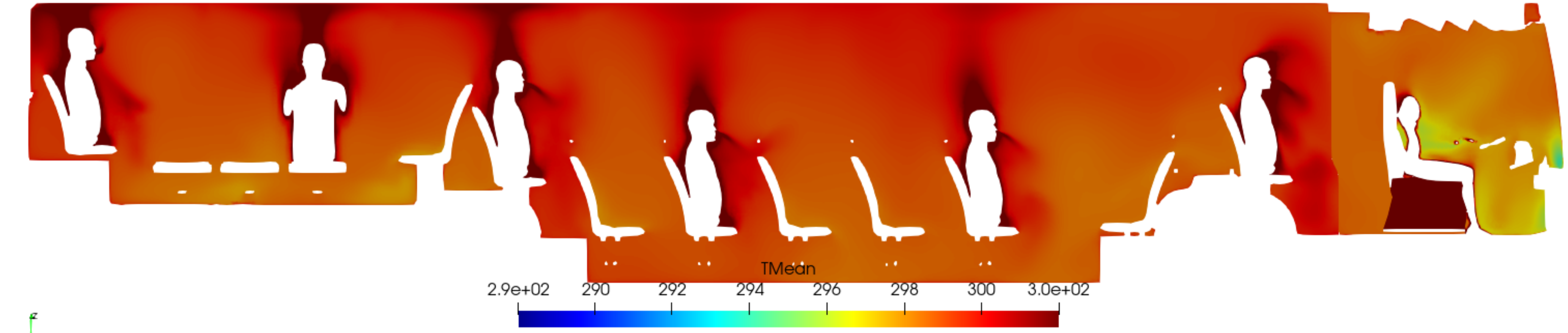
Volume Average of Age of Air: 80 s



CFD Results

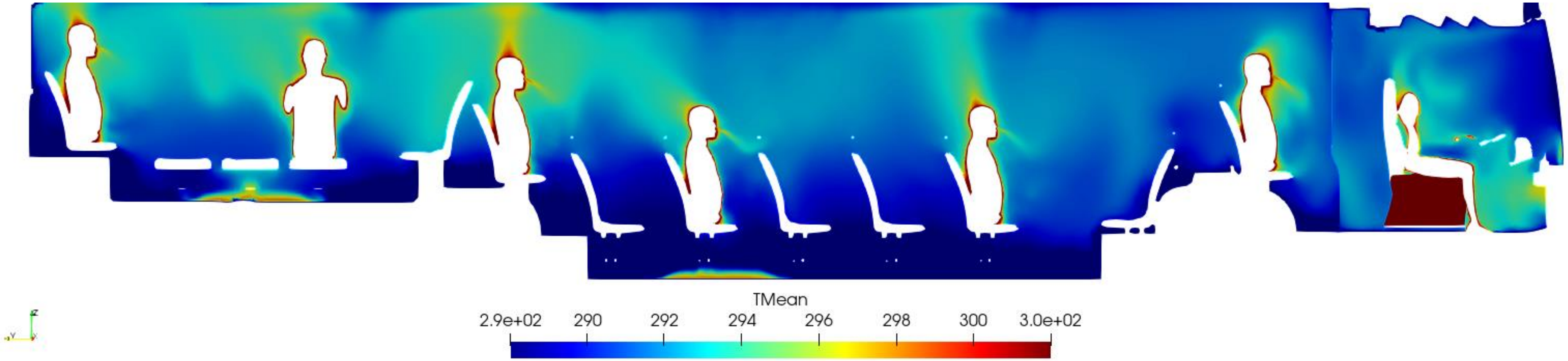
low-occupancy / no-mask (DoE 01)

Run 03 (hot/55%/speaking)



Temperature: 15-29 °C

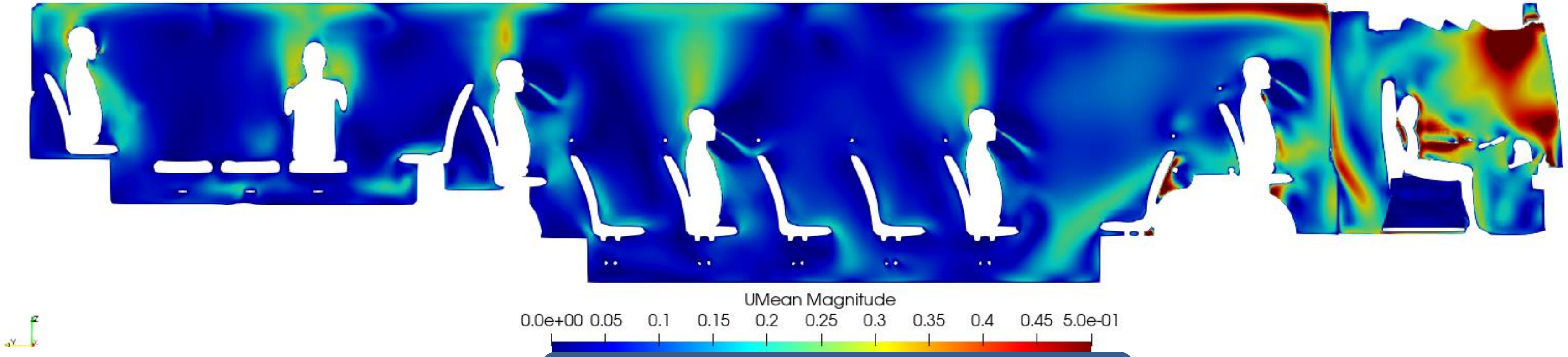
Run 10 (cold/100%/breathing)



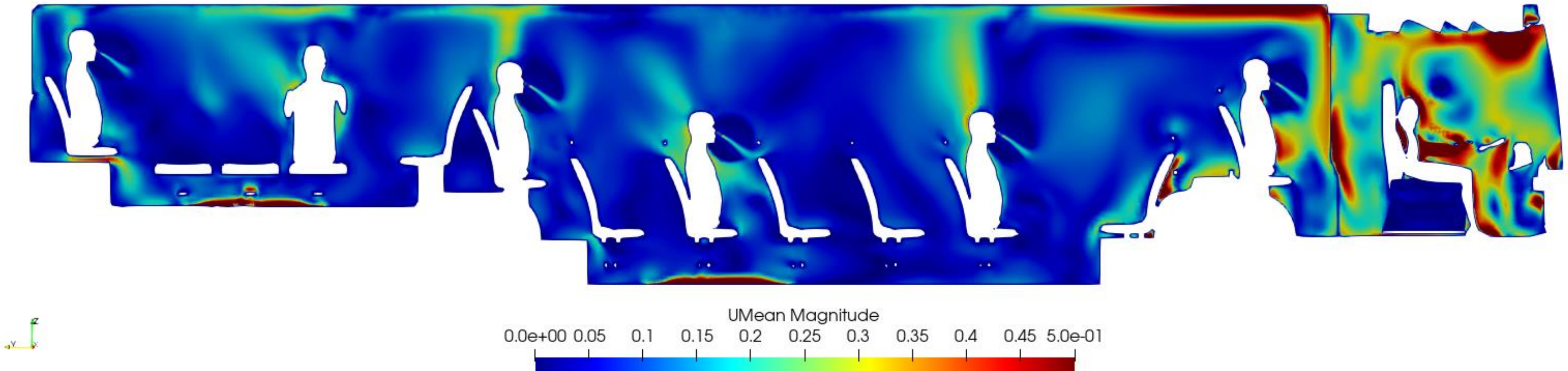
CFD Results

low-occupancy / no-mask (DoE 01)

Run 03 (hot/55%/speaking)



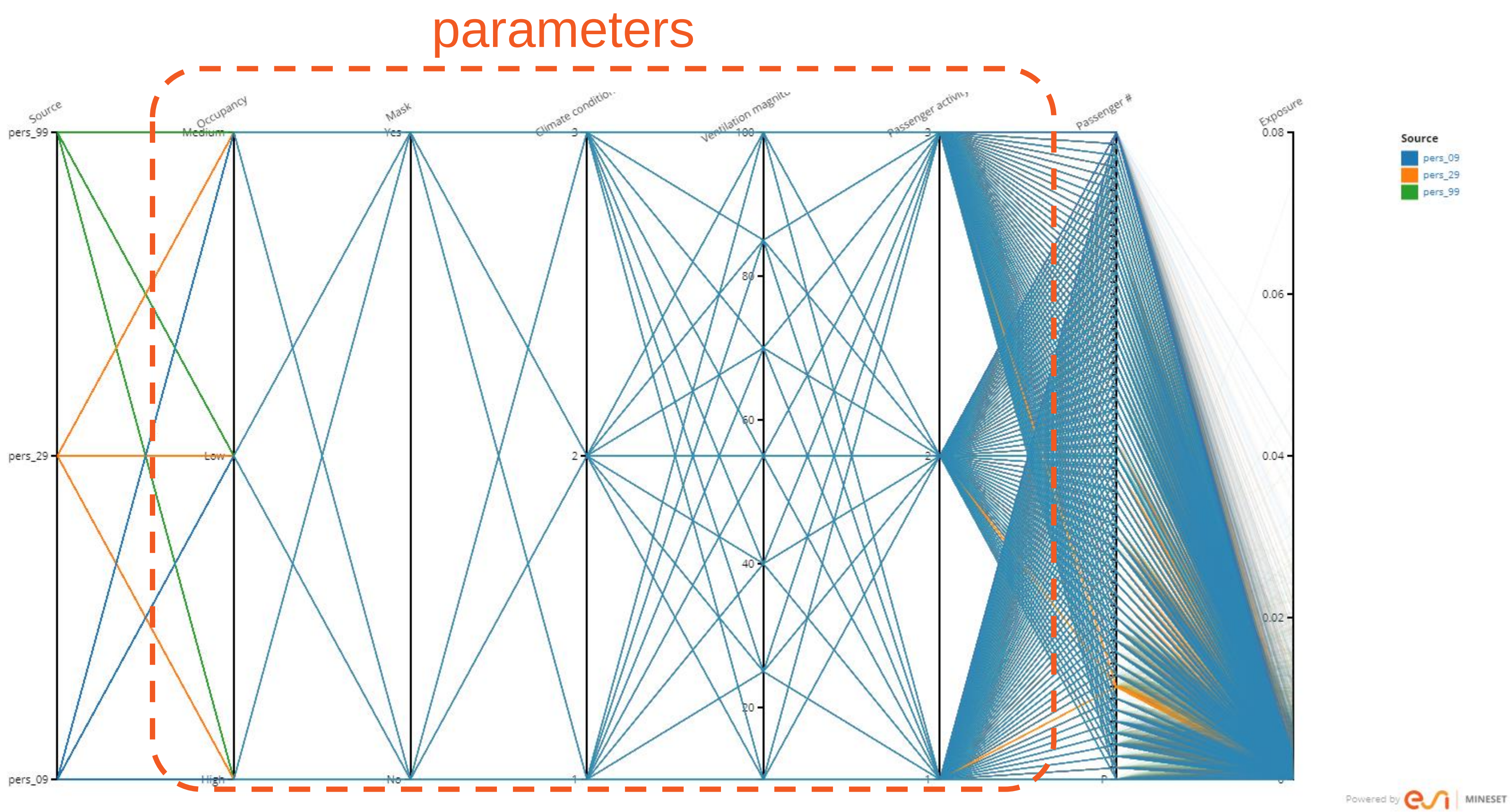
Run 10 (cold/100%/breathing)

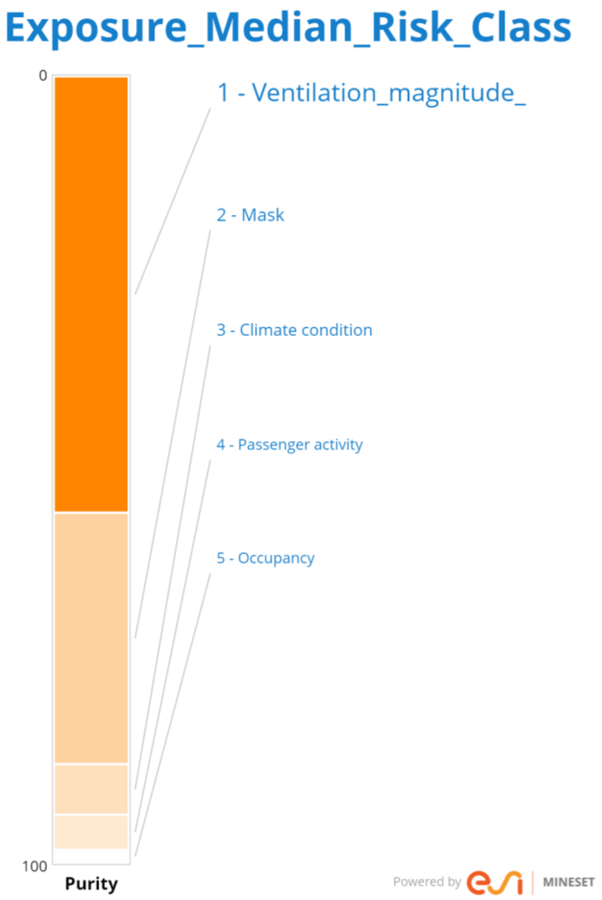


ROM Results / Data Analytics

Parallel Coordinates

Column Importance

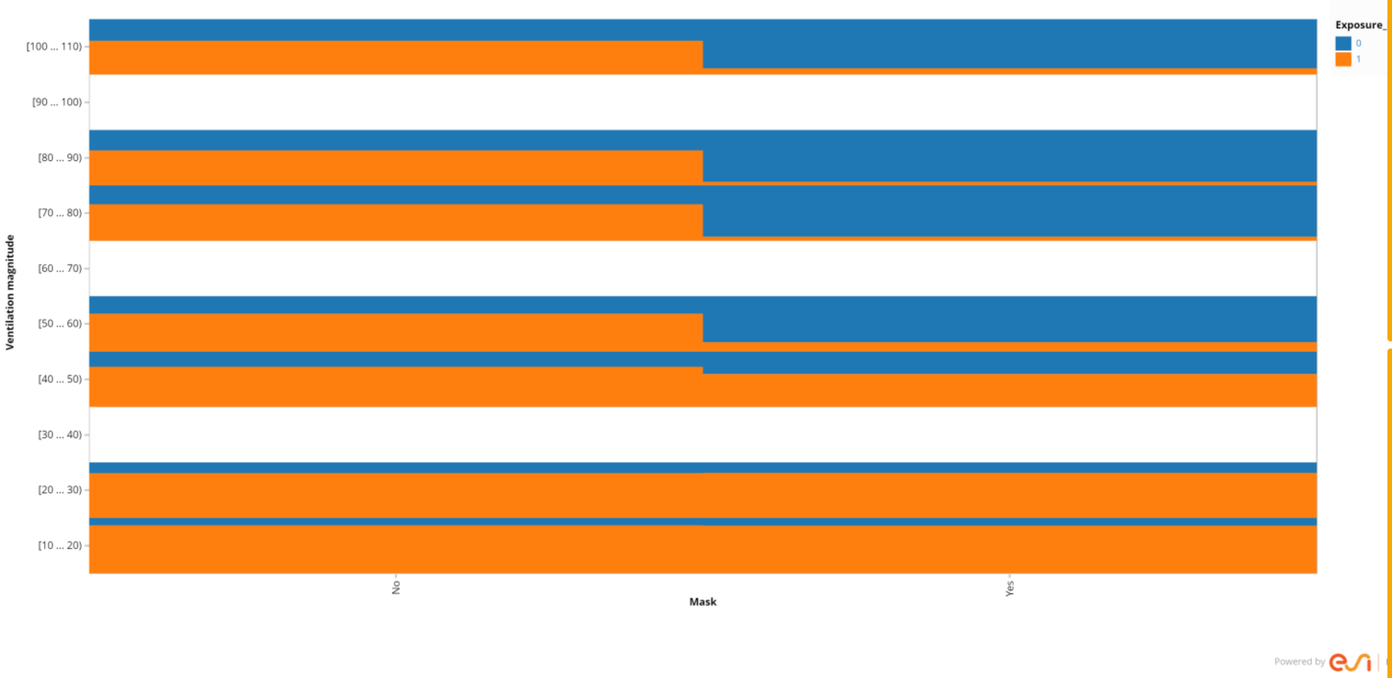


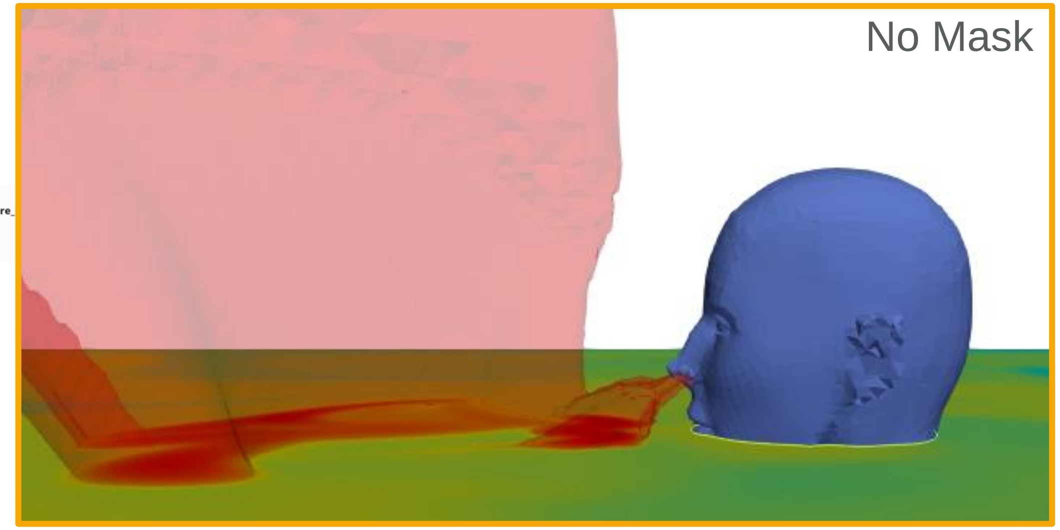


ROM Results / Data Analytics

Heat Map

IsoVolume of
c_09>0.001

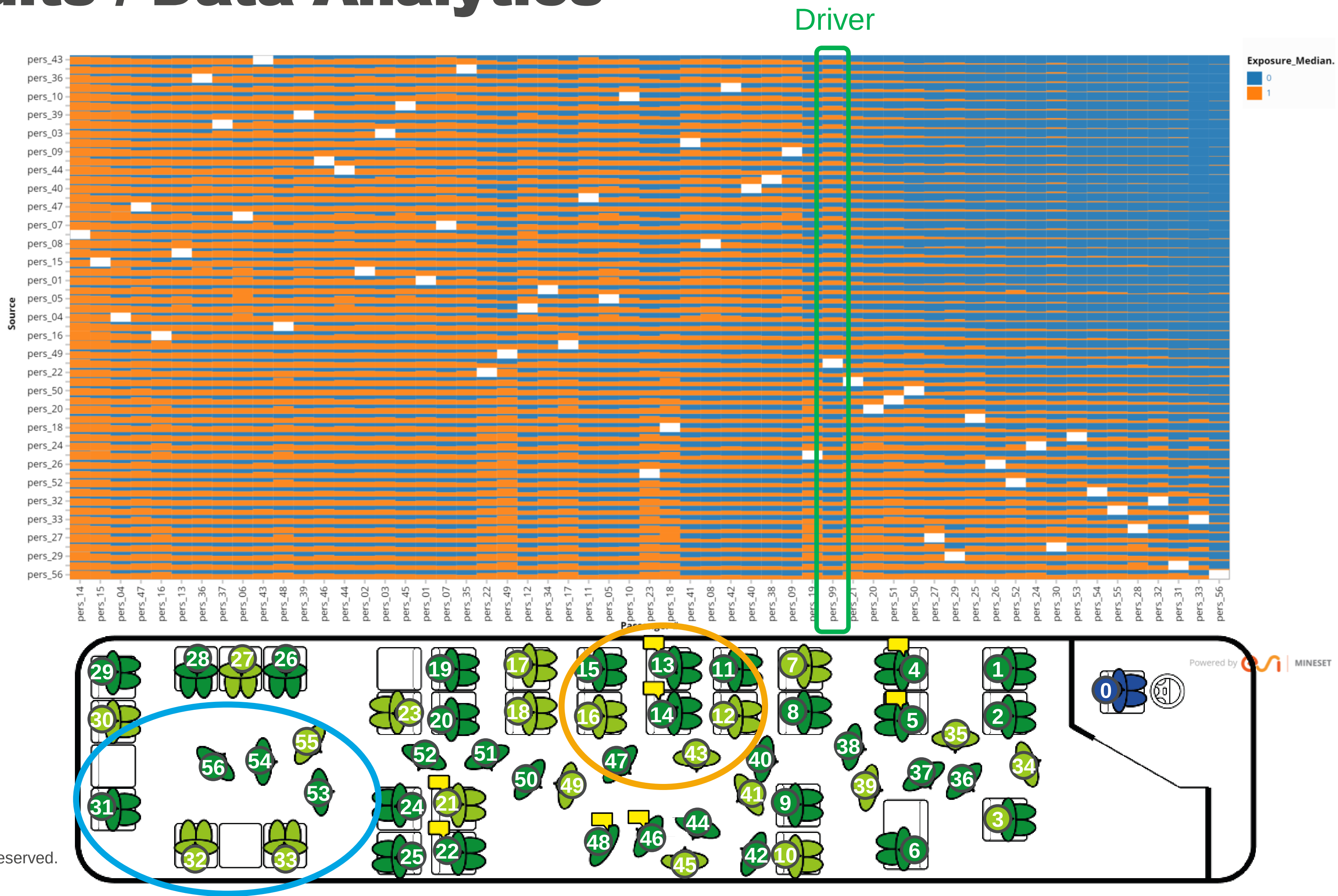




Parallel Coordinates

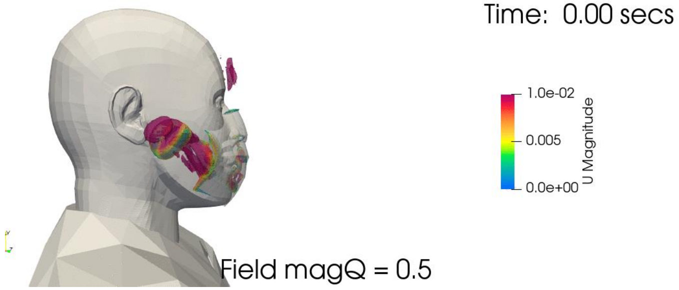
ROM Results / Data Analytics

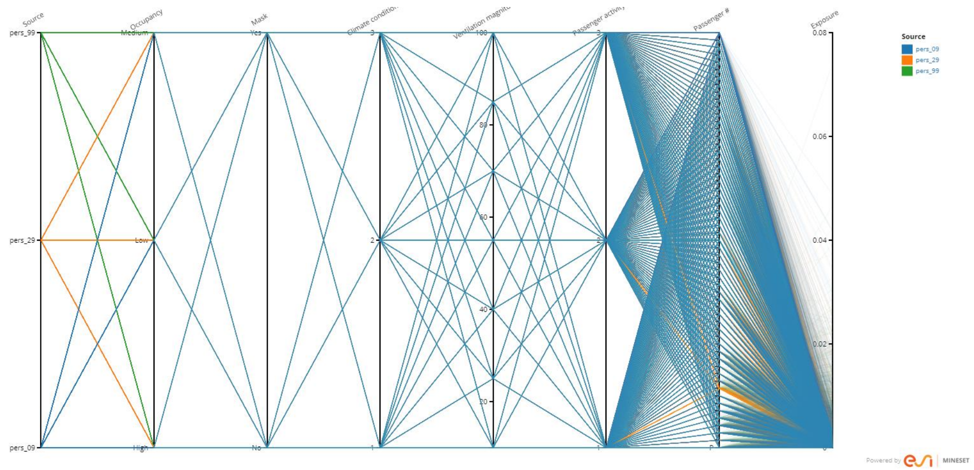
Heat Map



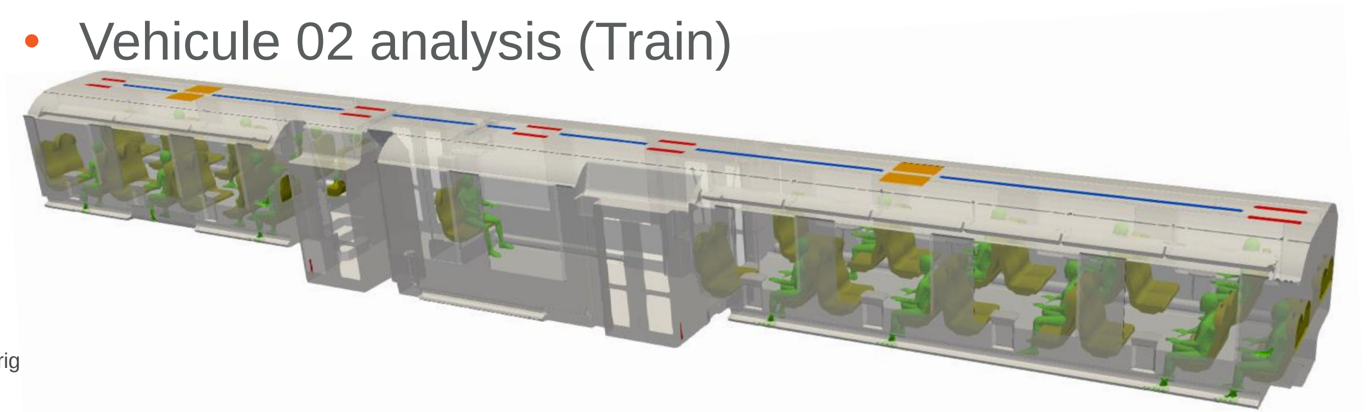
Summary & Outlook

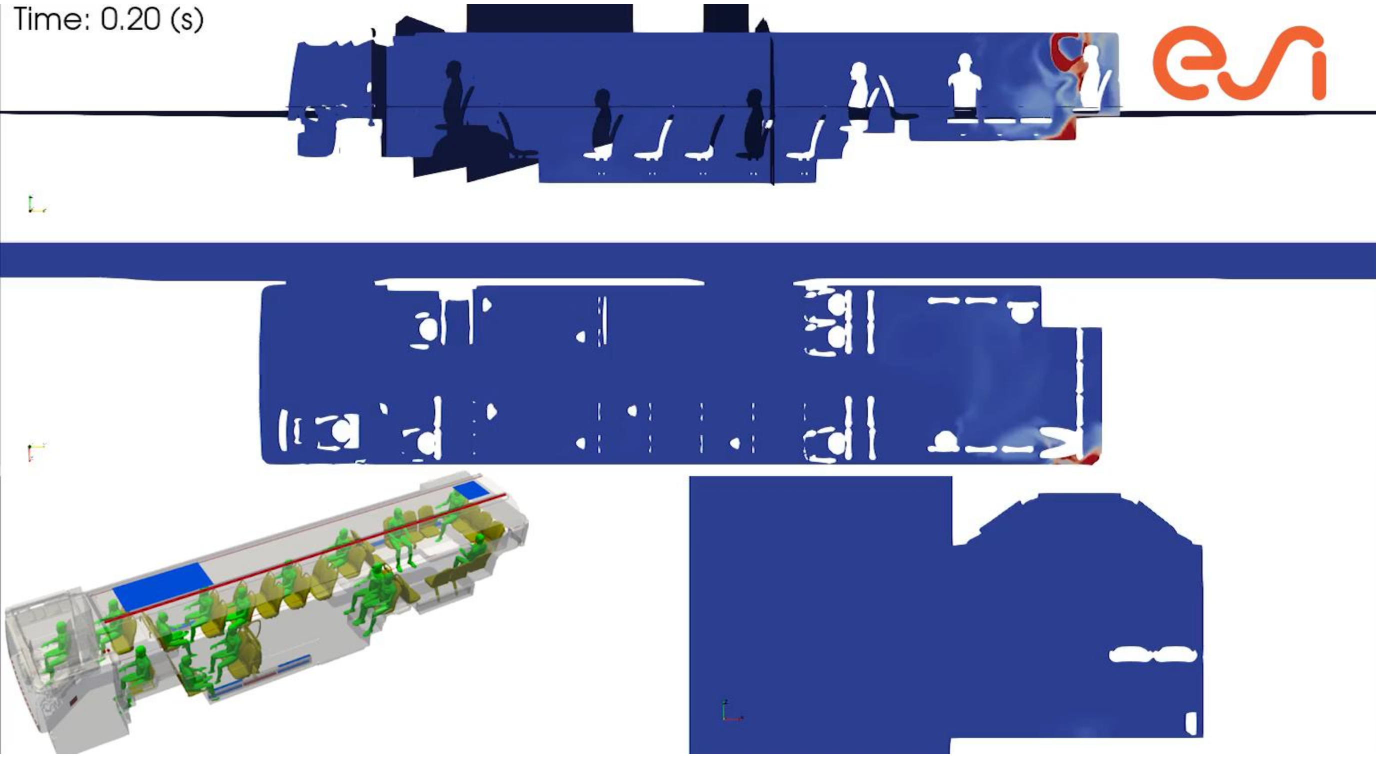
- **Summary**
  - CFD Methodology and automated process implemented for breathing/talking/shouting with and without mask scenario
  - Update the MOR solver to handle reciprocity matrix (csv format)
  - Results evaluate via data analytic tool
    - Most influencing parameters
  - Analyze effect of door opening (transient simulation)





- **Outlook**
  - Vehicule 02 analysis (Train)





Any Questions?

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