NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

TRB Webinar: Mitigate Exposure to Airborne Diseases through Bus Cabin Air

April 10, 2025

2:00 – 3:30 PM

PDH Certification Information

1.5 Professional Development Hours (PDH) – see follow-up email

You must attend the entire webinar.

Questions? Contact Andie Pitchford at TRBwebinar@nas.edu

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Program. Credit earned on completion of this program will be reported to RCEP at RCEP.net. A certificate of completion will be issued to each participant. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the RCEP.

ENGINEERING RCEP REGISTERED CONTINUING EDUCATION PROGRAM

AICP Credit Information

1.5 American Institute of Certified Planners Certification Maintenance Credits

You must attend the entire webinar

Log into the American Planning Association website to claim your credits

Contact AICP, not TRB, with questions

Purpose Statement

This webinar will explore effective strategies to mitigate the transmission of airborne viruses in bus cabins. Presenters will share insights from experimental and simulation studies on bus cabin air circulation, evaluating the effectiveness of various mitigation methods.

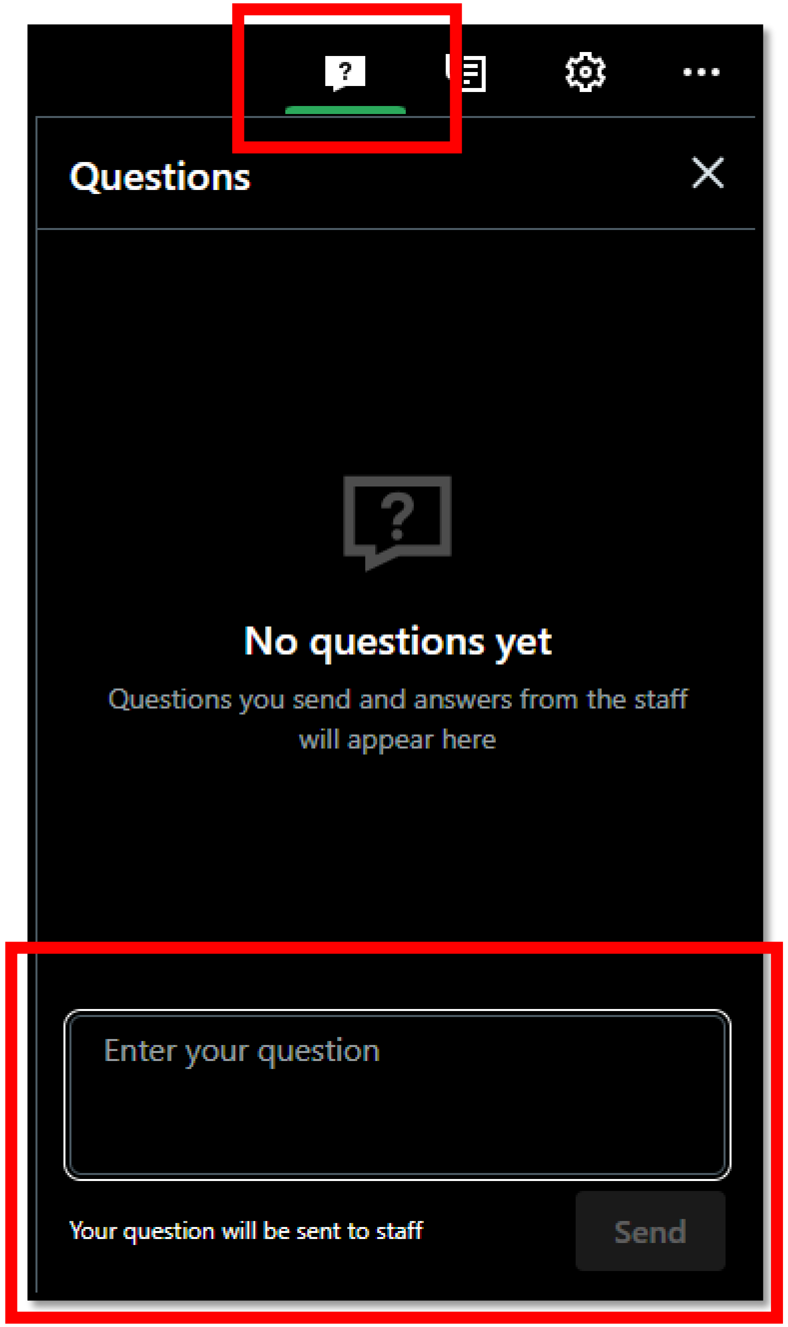
Learning Objectives

At the end of this webinar, you will be able to:

- Reduce exposure to airborne viruses in public transportation

Questions and Answers

- Please type your questions into your webinar control panel
- We will read your questions out loud, and answer as many as time allows



Today's presenters

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Mitigate Exposure to Airborne Diseases for Public Transportation Passengers and Employees with Focus on Bus Cabin Air Systems

Heejung Jung (UCR) and Jacob Swanson (MSU)

UC RIVERSIDE

Department of Integrated Engineering
MINNESOTA STATE UNIVERSITY, MANKATO

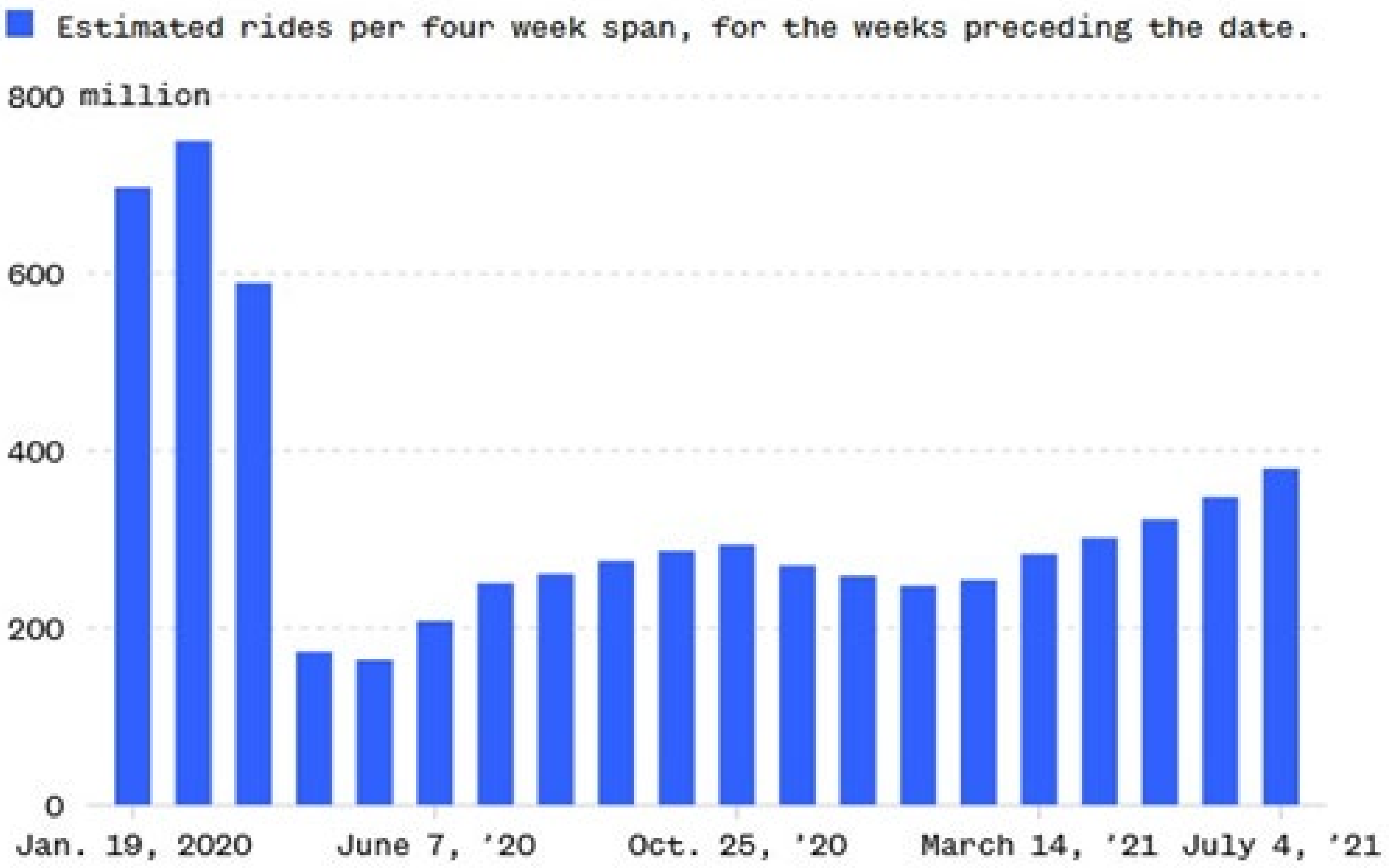
Acknowledgements

- National Academy of Science, Engineering, and Medicine for funding: TCRP F-30
- Panel members and TCRP staff (Dianne Schwager)
- Staff from MSU. In particular:
  - Anne Kerber
  - Kevin Dover
- Students from MSU and UCR. In particular:
  - Branda Lopez, Evan Renck (UCR)
  - Joey Stam (MSU)
  - Many others*
- LA Metro and CE-CERT for the loan of test buses

*John Nutt, Cosku Kaplan, Mohamed Abdi, Brendan Dykes, Sam Merchant, Yeng Moua, Tate Putman, Bryan Chen, Megan Lee

Background

The pandemic caused ridership for public transportation to plummet due to the fear of air transmission of COVID-19 among passengers



NBC News, 2021

Evolution of responses for bus through the pandemic

Per CDC

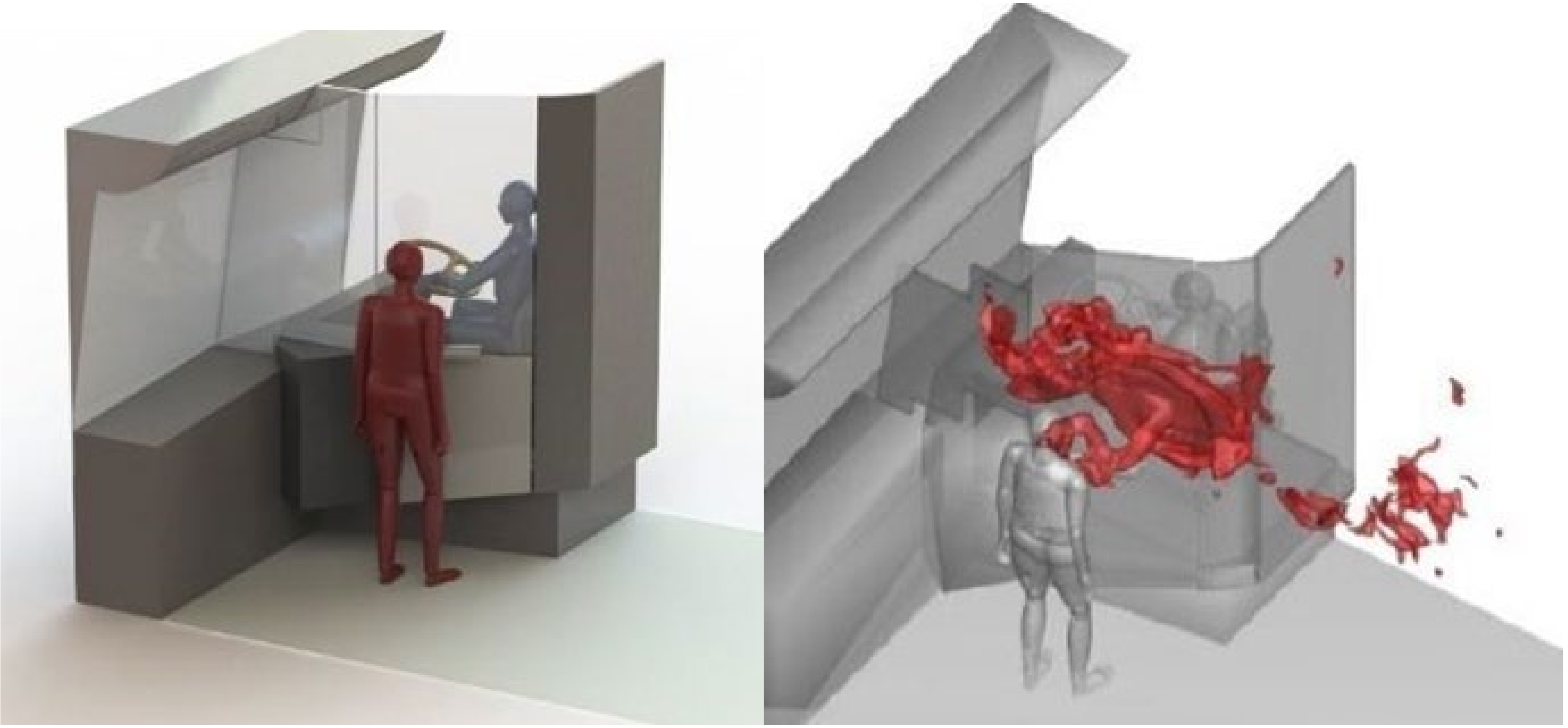
- Surface cleaning
- Social distancing (6 ft rule) and mandate of wearing masks

Per request by operators and customers

- Clear partitions
- UV cleaners
- HEPA filters

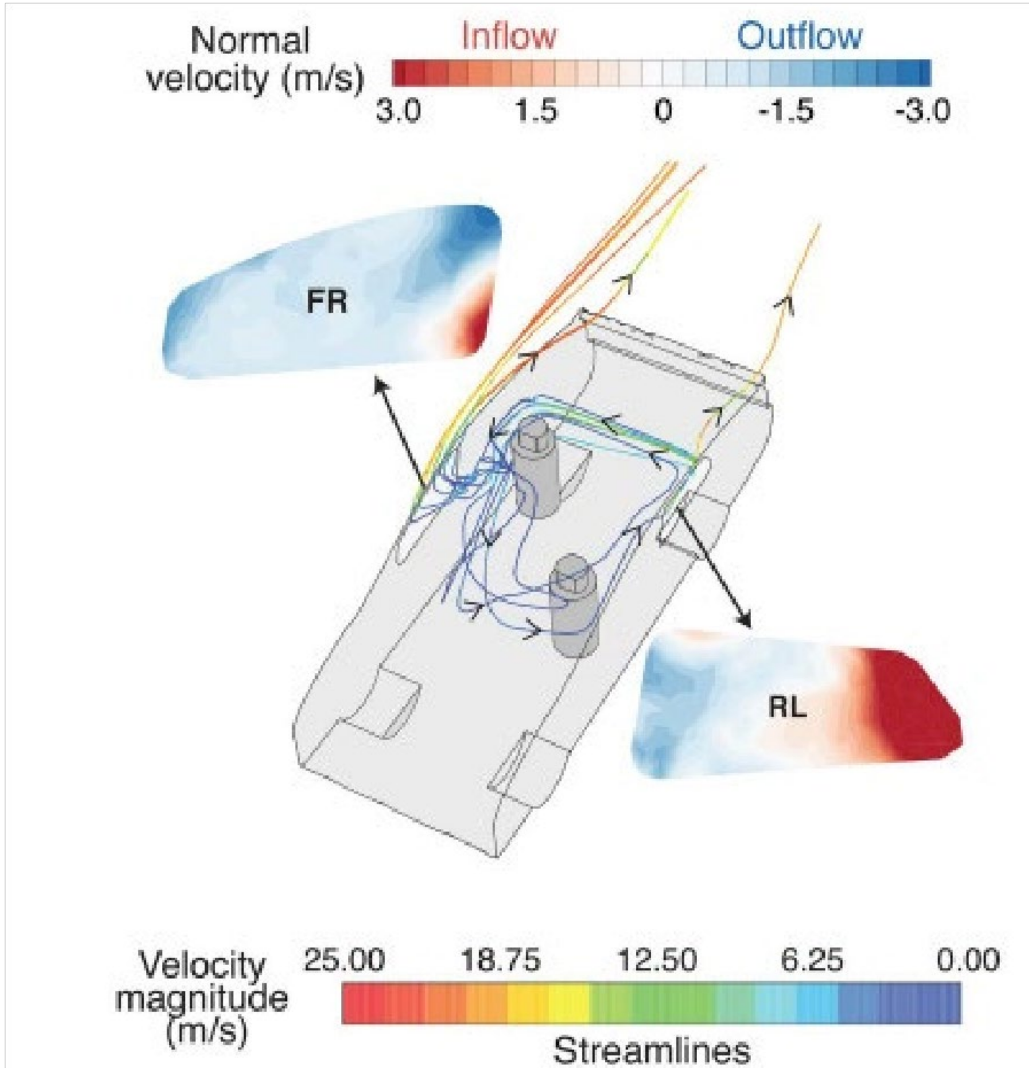
Previous studies

The effect of clear barriers



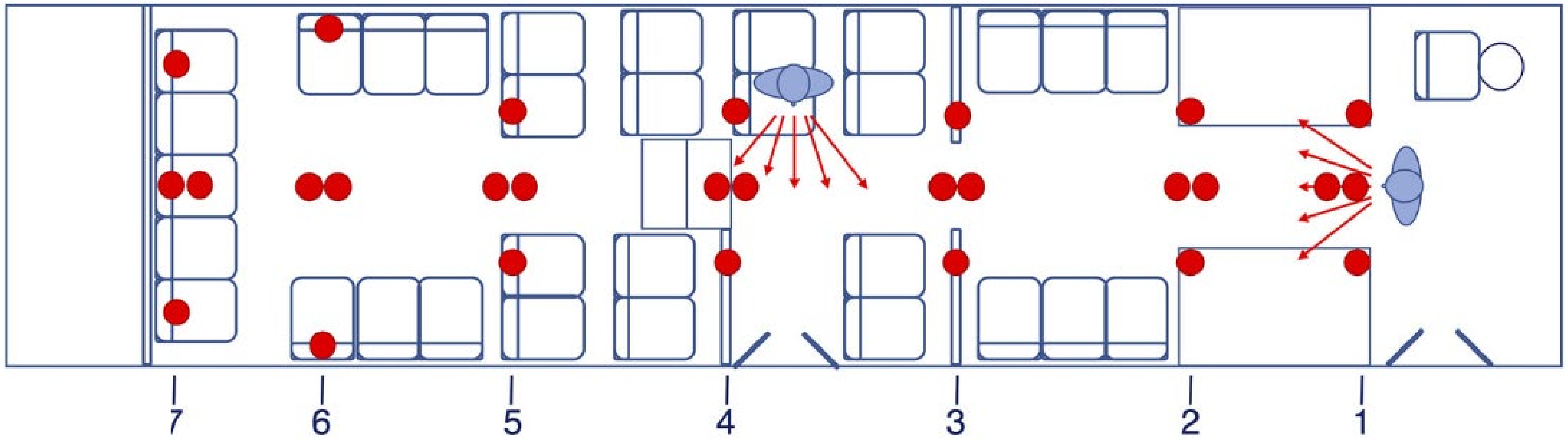
University College London using Computational Fluid Dynamics, 2021

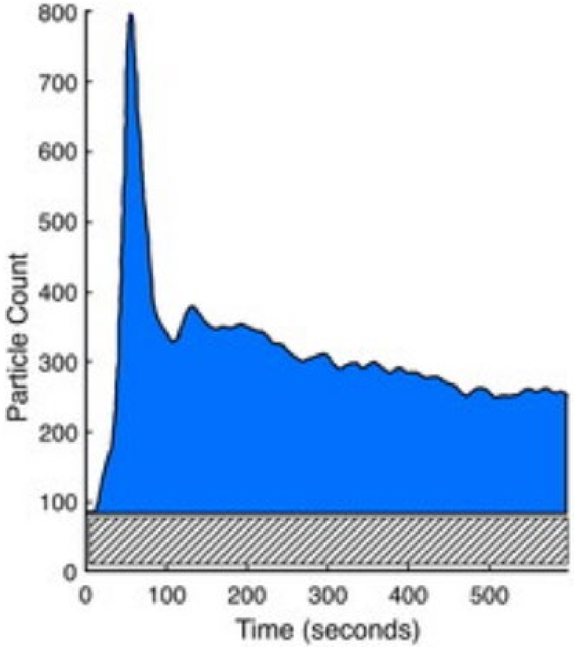
The effect of opening windows



Mathai et al., 2021, Brown Univ.

Aerosol dispersion study

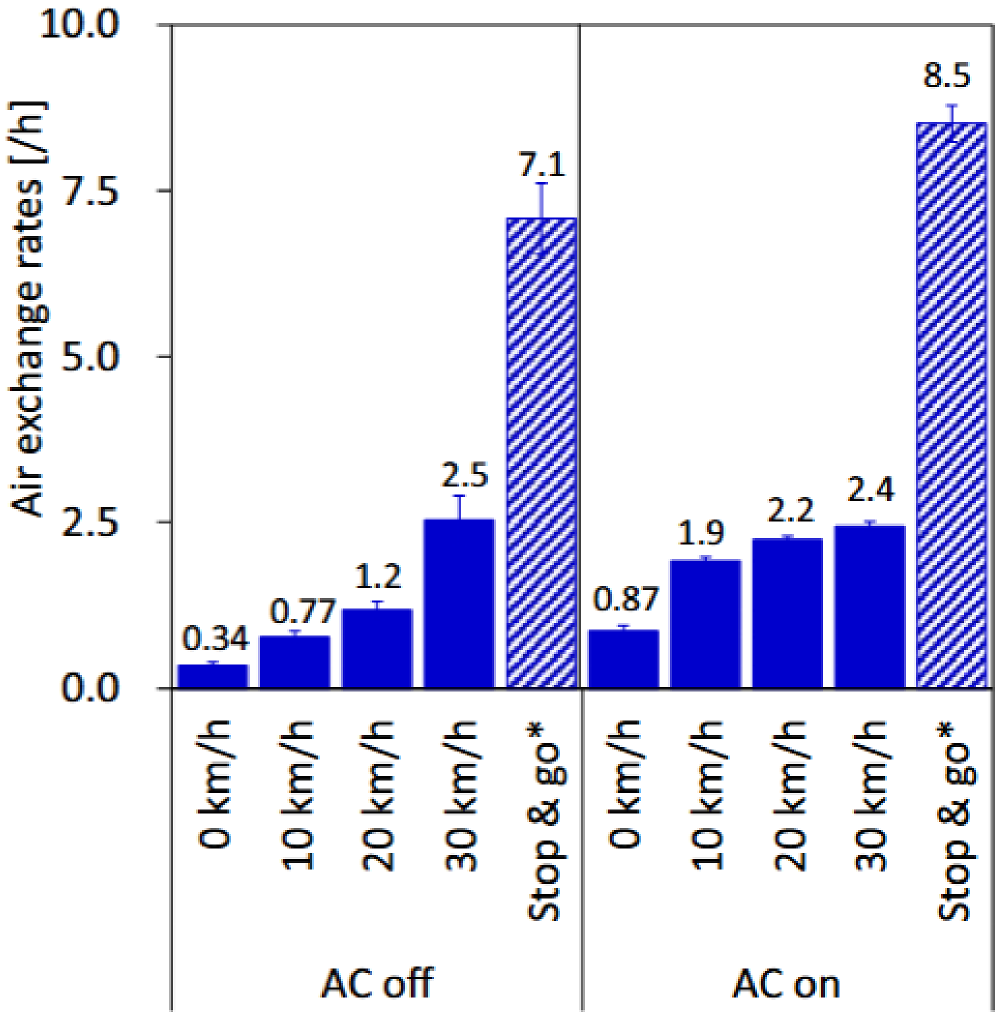




Aerosol arrival time

Edwards et al., 2021, MITRE Corporation

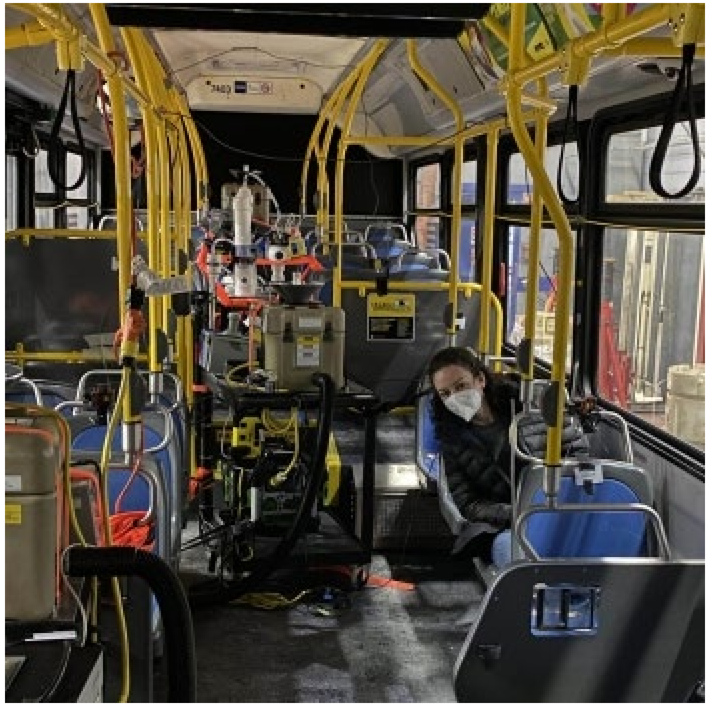
Measurement of Air Exchange Rate as a function of vehicle speed

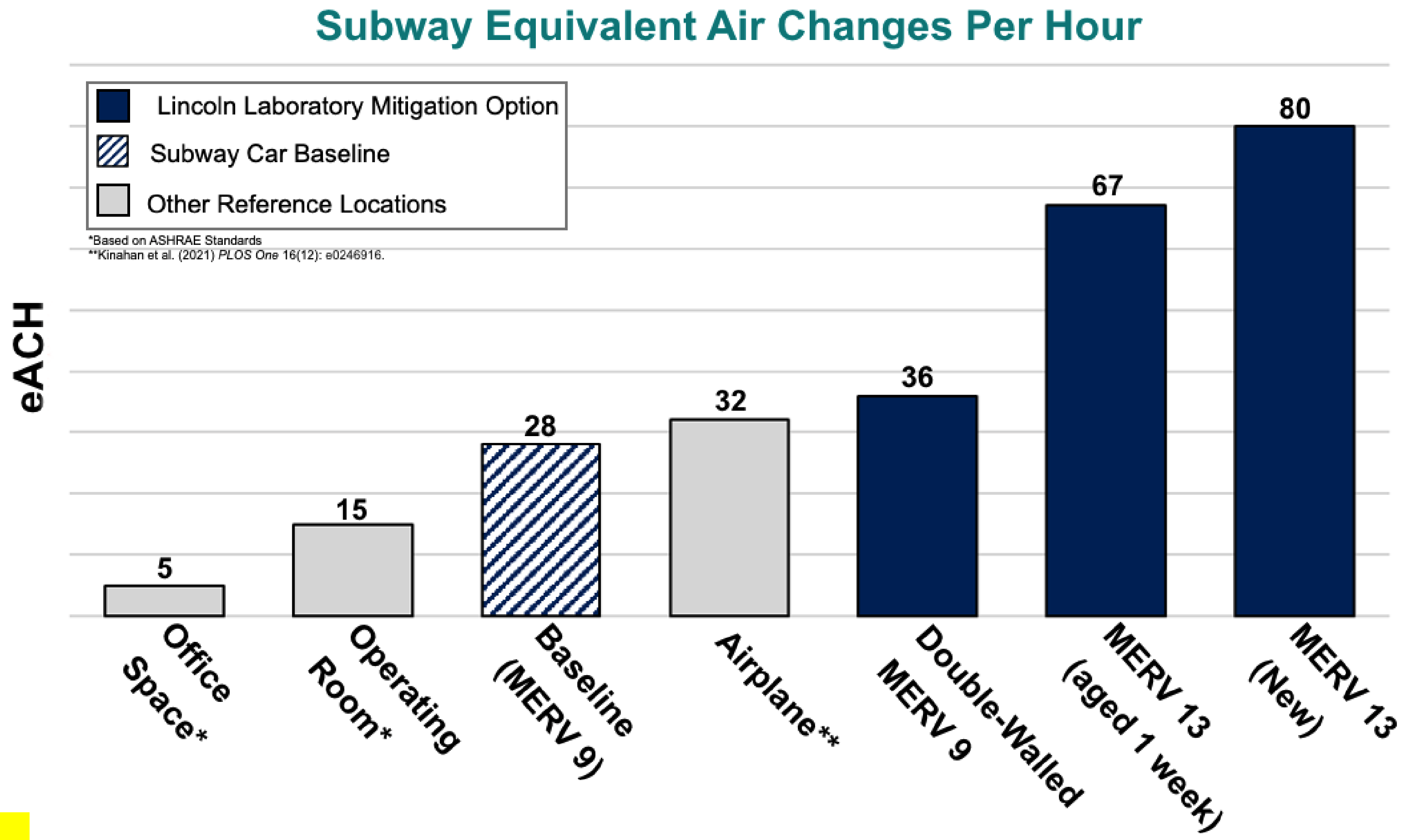


Stop & go test: the bus repeatedly moved 500 m at 30 km/h and then stopped and opened the door for 20 s.

Shinohara et al. 2021, AIST in Japan

Measurement of simulated Covid-19 removal rate in subway cabin





Ramsey et al., 2020-2024, MIT Lincoln lab

This result came out after our study.

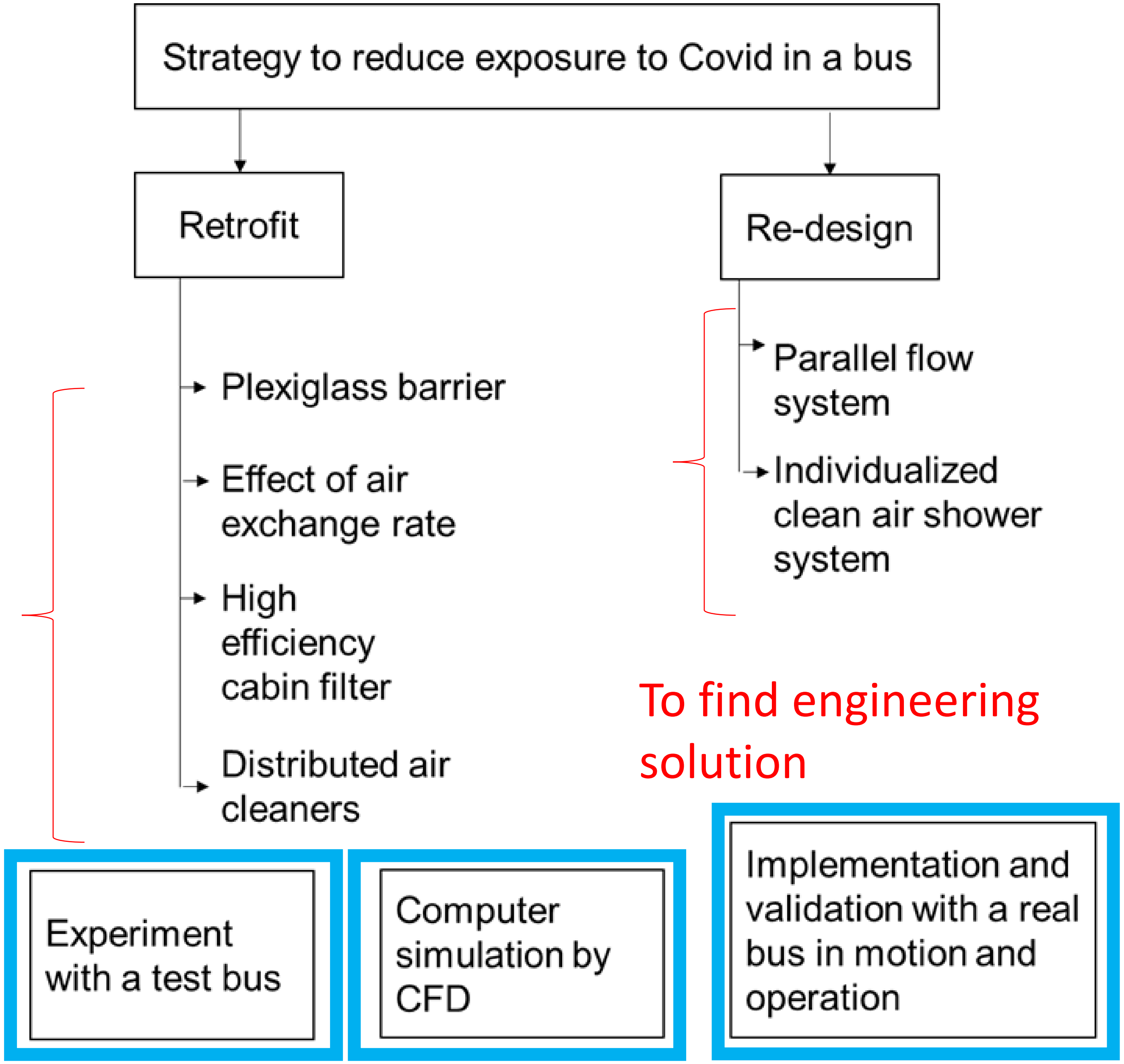
Missing questions in previous studies

- What is the most effective remediation method?

- Is there any engineering solution?

Objectives of the study

To determine most effective method



Acquisition and preparation of the test bus

Bus #1

North American Bus Industries (NABI) 2002 test vehicle

Make	**North American Bus Industries (NABI)**
Model	40-LFW
Vehicle Type	Transit Bus
Gross Vehicle Weight Rating (GVWR)	40,600 lbs
Fuel Type	Hybrid - CNG
Cabin Volume	57.25 m^3

NABI 2002 Test Vehicle Specifications

Acquisition and preparation of the test bus

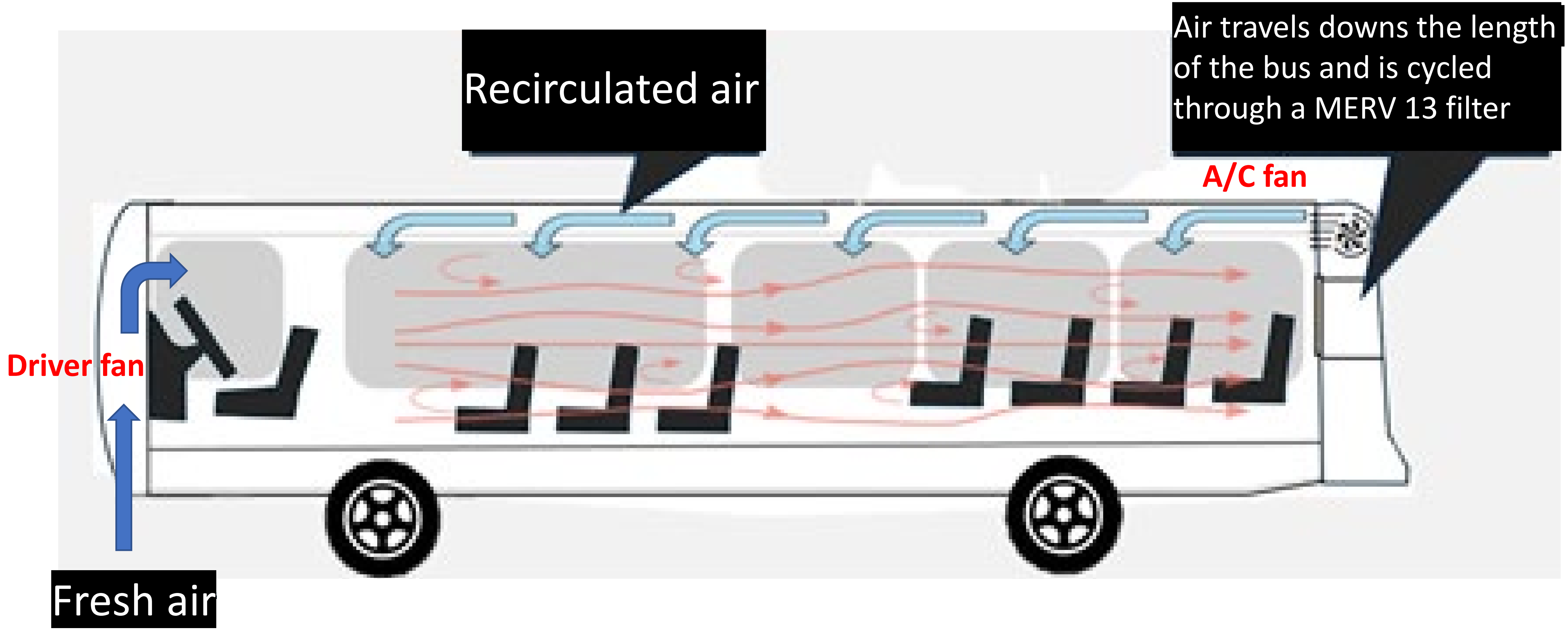
Bus #2

LA Metro 45C North American Bus Industries (NABI) 2008 Test Vehicle.

Make	North American Bus Industries (NABI)
Model	CLFW
Vehicle Type	Transit Bus
Gross Vehicle Weight Rating (GVWR)	30,130 lbs
Fuel Type	CNG
Cabin Volume	71.15 m^3

LA Metro 2008 Test Vehicle Specifications

Ventilation system of the intracity buses (e.g. bus #1 and #2)



CO_2 canister

Low cost air quality monitor for PM and CO_2

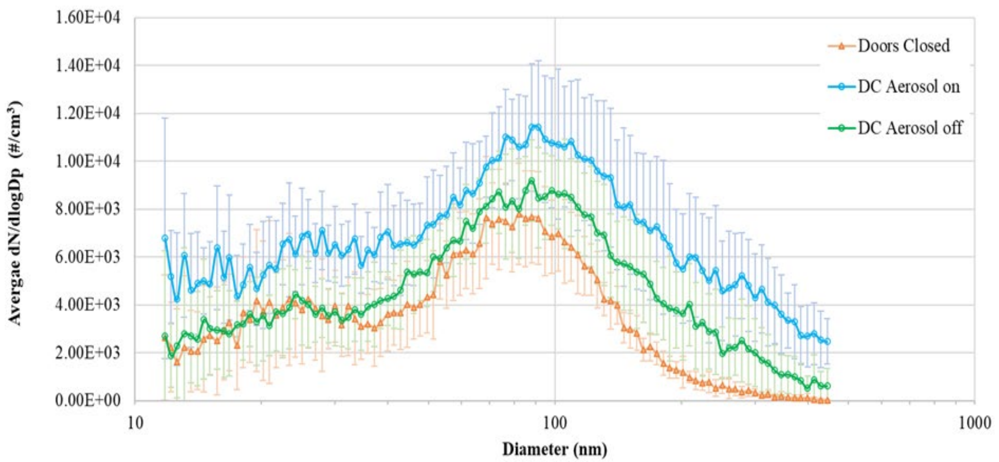
TSI AirAssure

Generation and dispersion of COVID-like test aerosol

- Two generators built
- The expiration opening (1.2 in ID), opening angle (30°), expiration velocity (4.5 m/s) were based on human geometry and coughing respiratory events
- Salt / water continuous flow generator used in experiments

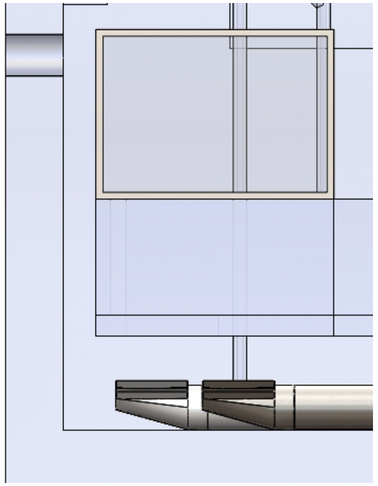
Generation and dispersion of COVID-like test aerosol

- The mean particle size immediately after exhalation ~ 1 µm
- After evaporation of water ~ 100 nm



Clear barriers were designed and built to confine the airflow as part of the “parallel flow” engineering solution

a) 

b) 

c) 

d) 

Effect of cabin air filtration improvements

- Step 1: Measure particle removal rate (eACH) using existing in-use MERV 13 filter

- Step 2: Measure particle removal rate using a new MERV 13 filter and compare.

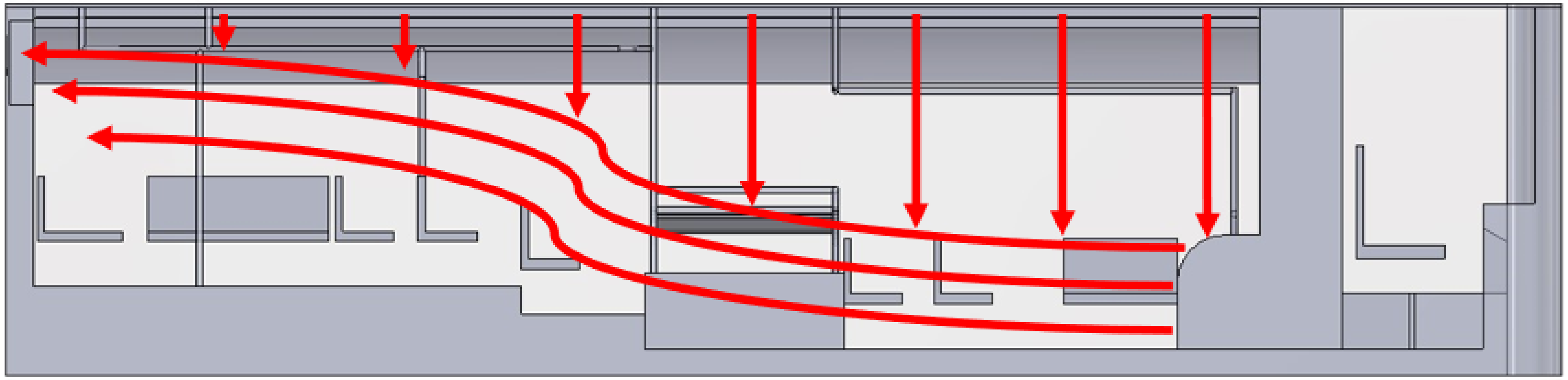
Effect of on-board air cleaners

Compare particle removal rate (eACH) with and without standalone HEPA filter air cleaner.

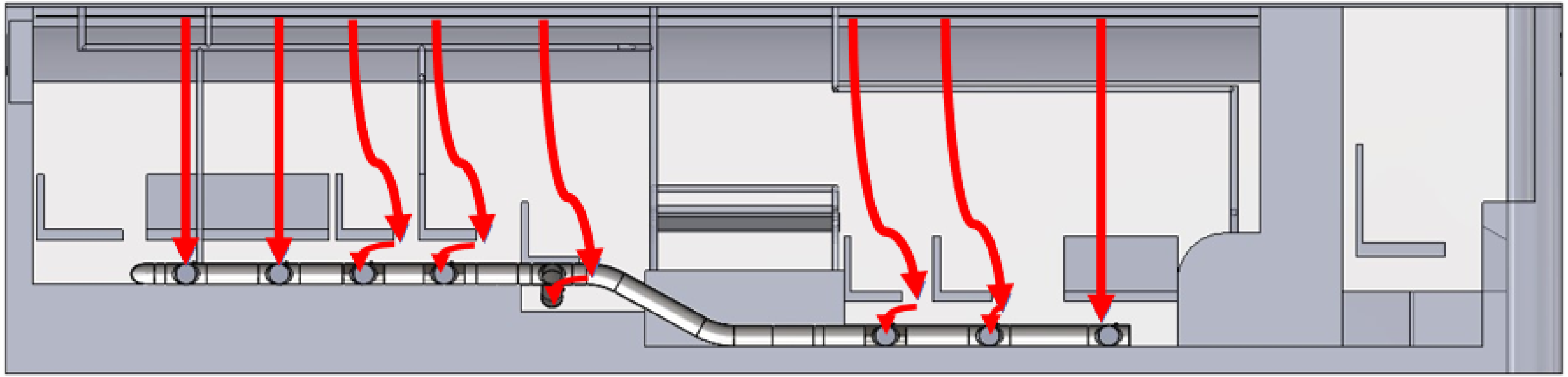
Two HEPA filter air cleaners were placed in the front middle and in the rear middle.

Honeywell True HEPA Air Purifier

Effect of ventilation design changes

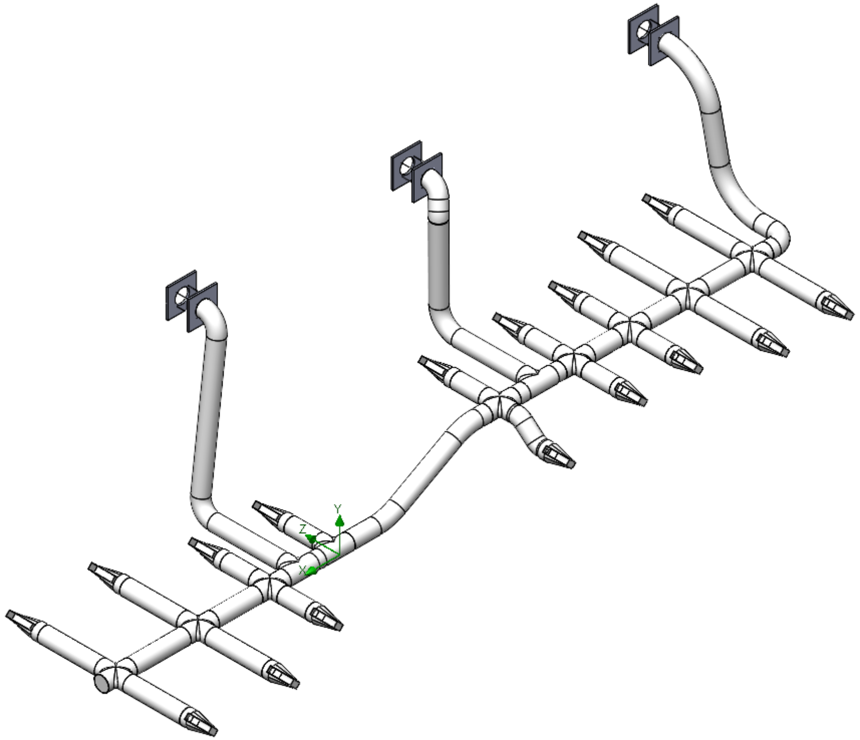


“Standard” bus flow configuration

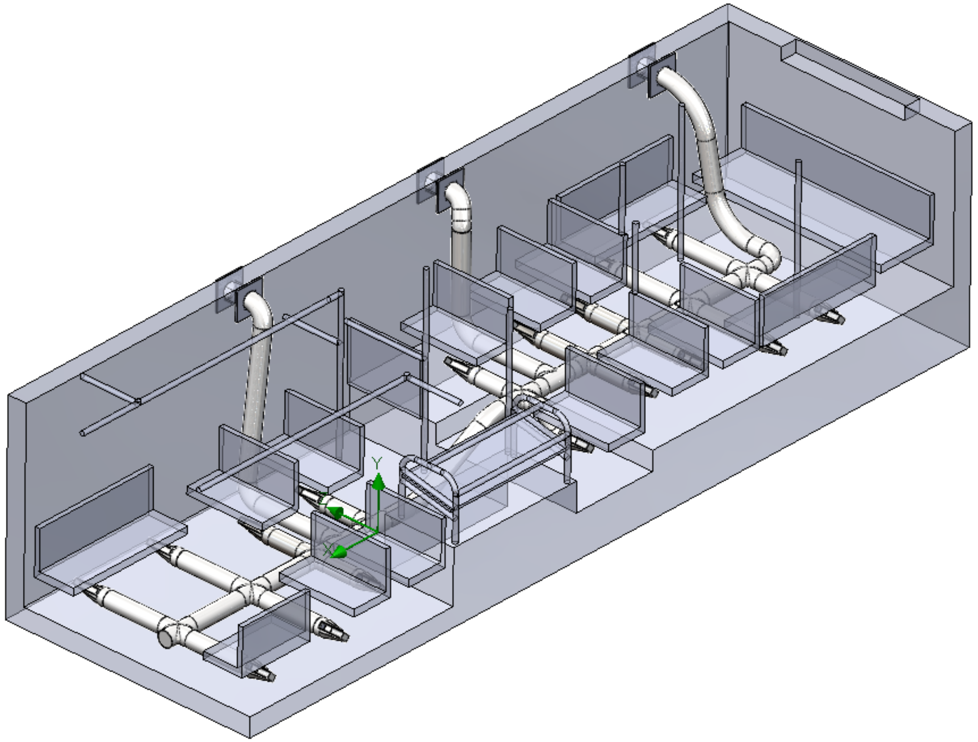


“Parallel flow” bus flow configuration

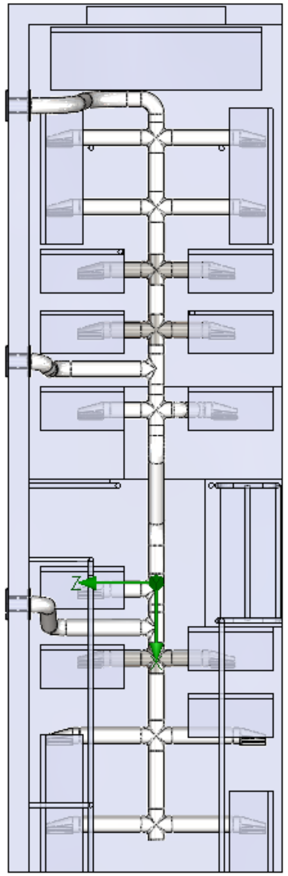
Parallel Ventilation System Design and Models



Lower Parallel Ventilation System



Ventilation System in Bus

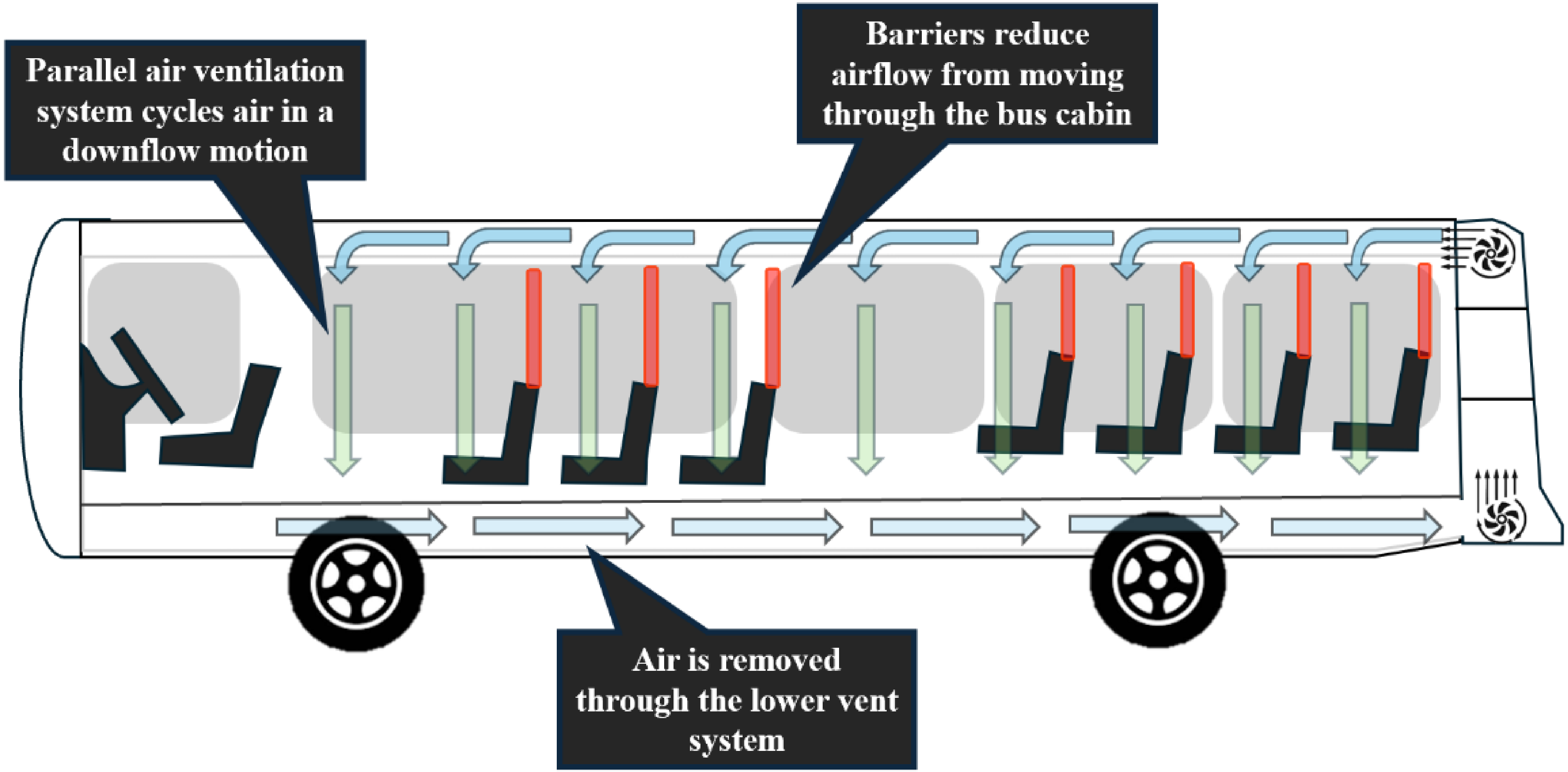


Top View of Bus with Ventilation System

“Parallel flow” ventilation system

“Parallel flow” ventilation system

The parallel system could be implemented in much simpler way in the production bus

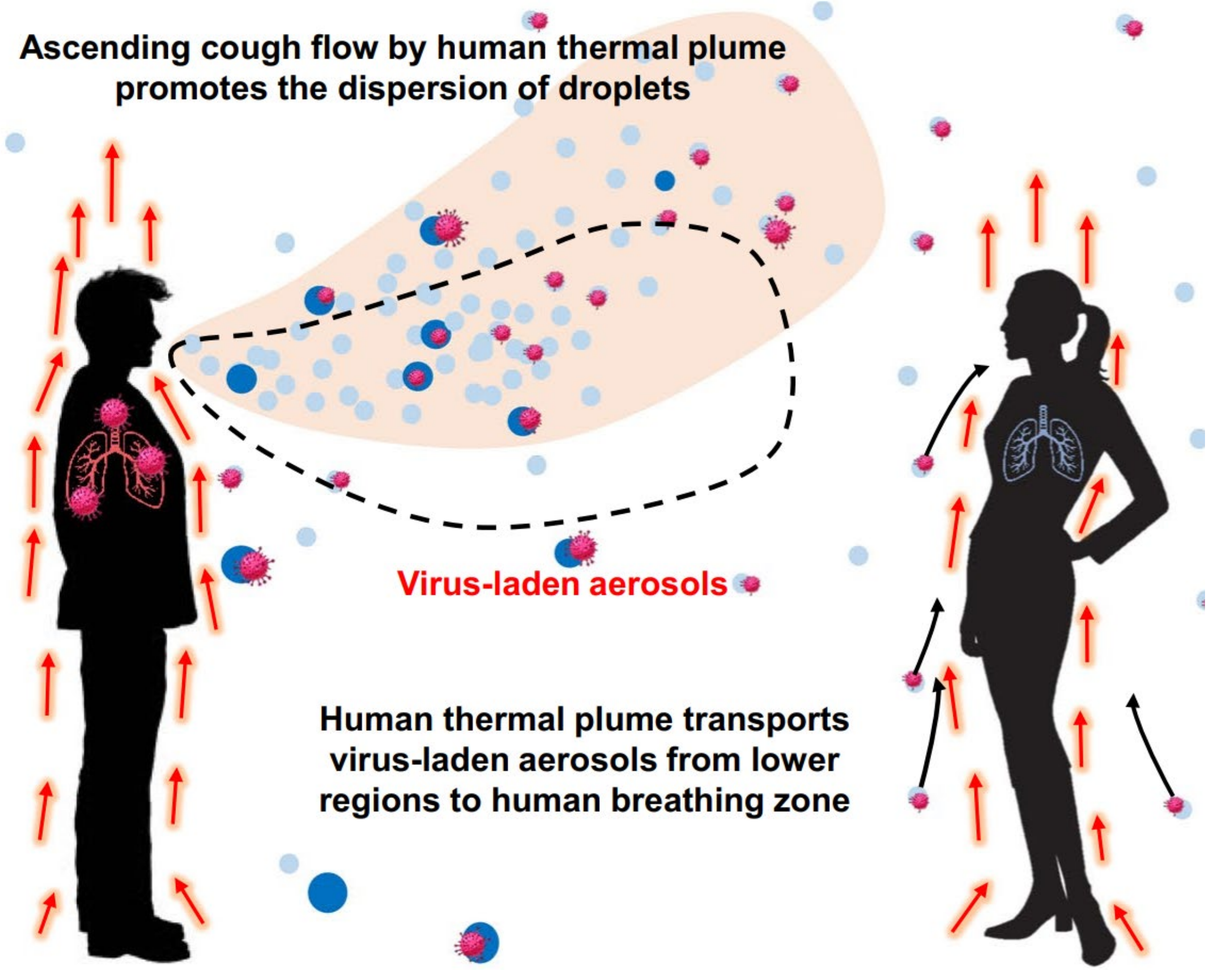


Pause for questions or comments re-design of the ventilation system

CFD analysis

- CFD = computational fluid dynamics. Use a computer program to predict airflows and transportation of particles
- Simulations include
  - Airflow color contour and vector plots in X, Y directions for multiple “Z” planes
  - Particle tracing study results – 1 µm particles were “released” and their trajectories were tracked
- Report contains
  - CFD methods, equations, mesh sensitivity
  - Full results for 24 “cases”
    - X and Y direction velocities
    - Cross section views
    - Particle analyses

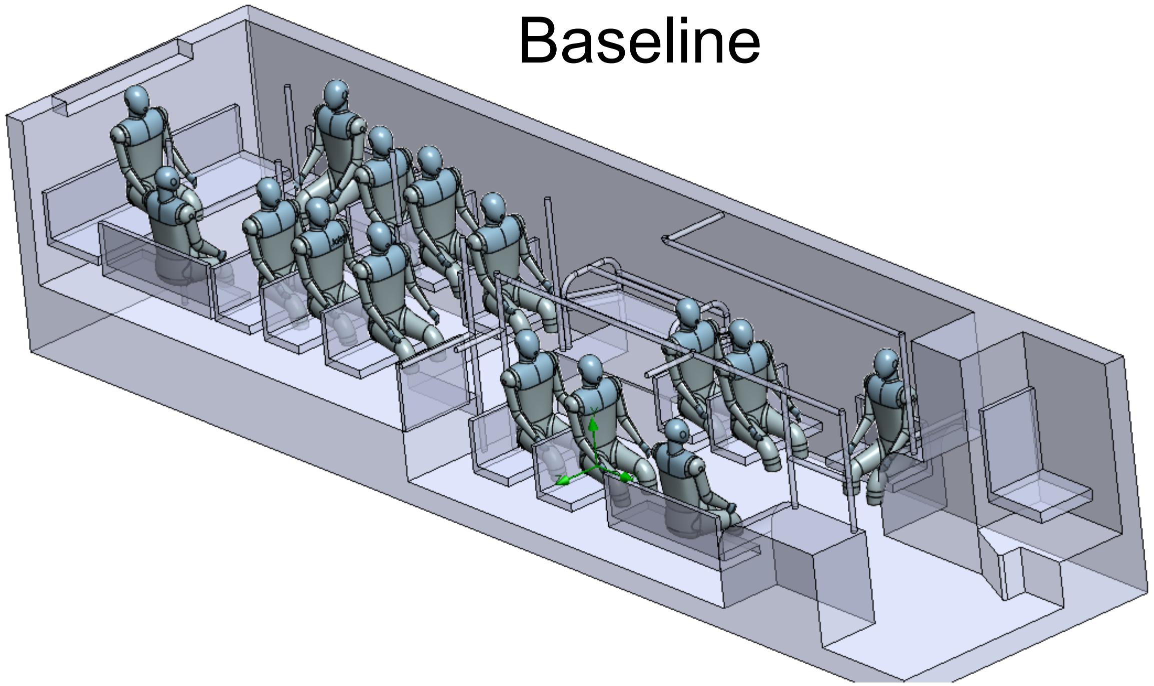
"Thermal plume" affects particle trajectories in the vicinity of a human



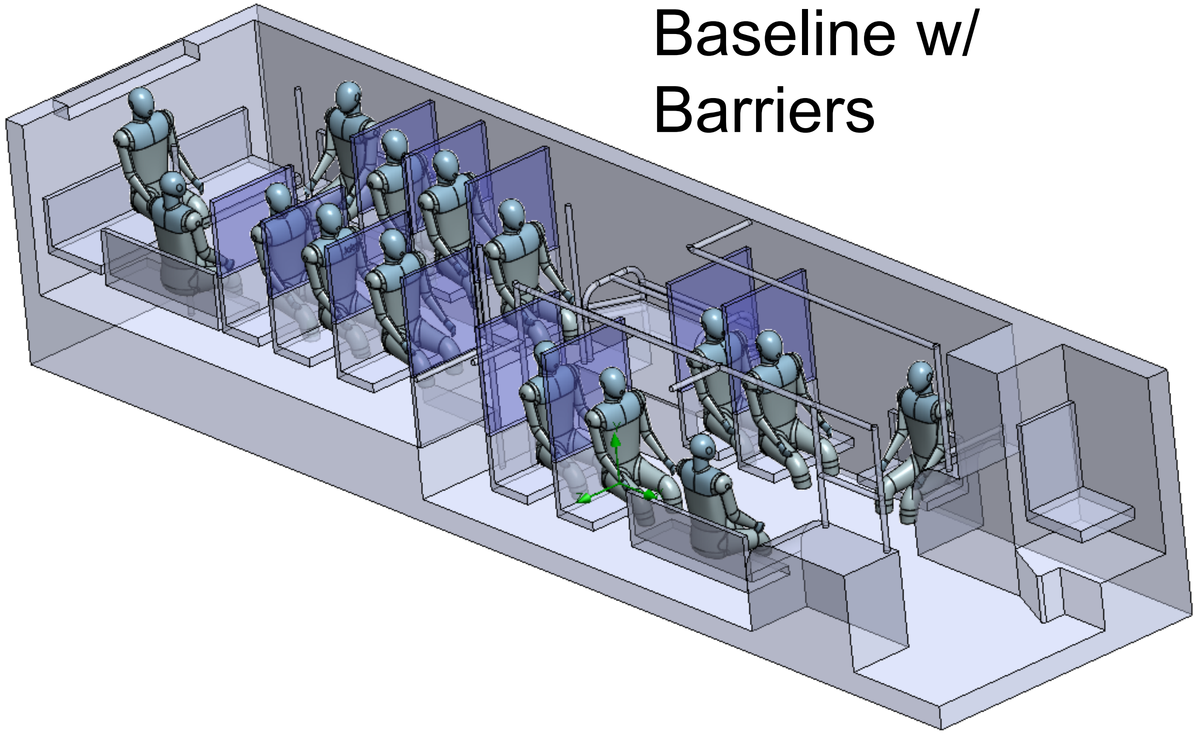
Environ Chem Lett. 2021; 19(3): 1971–1982

CFD configurations

Baseline



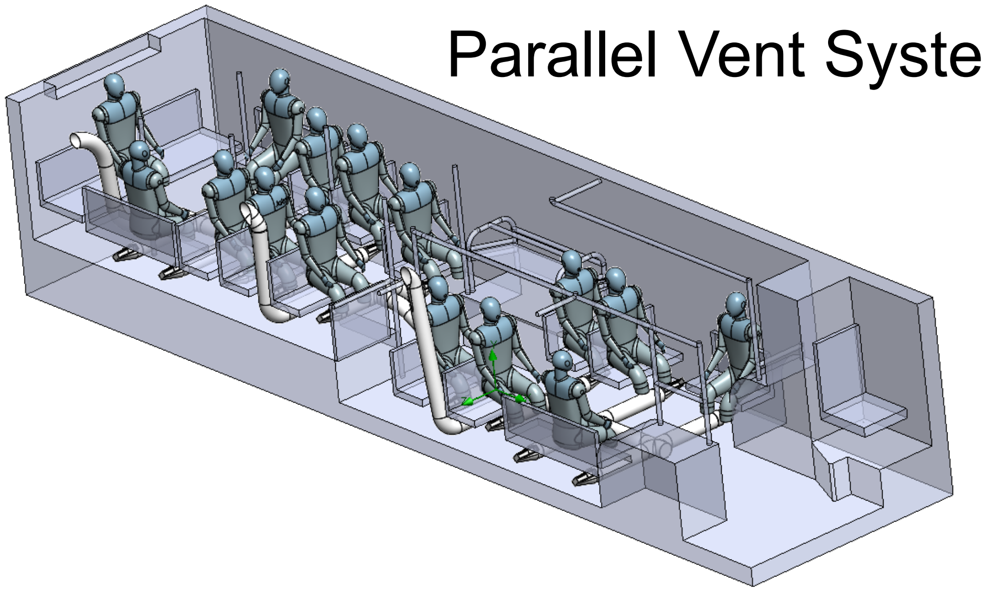
Baseline w/ Barriers



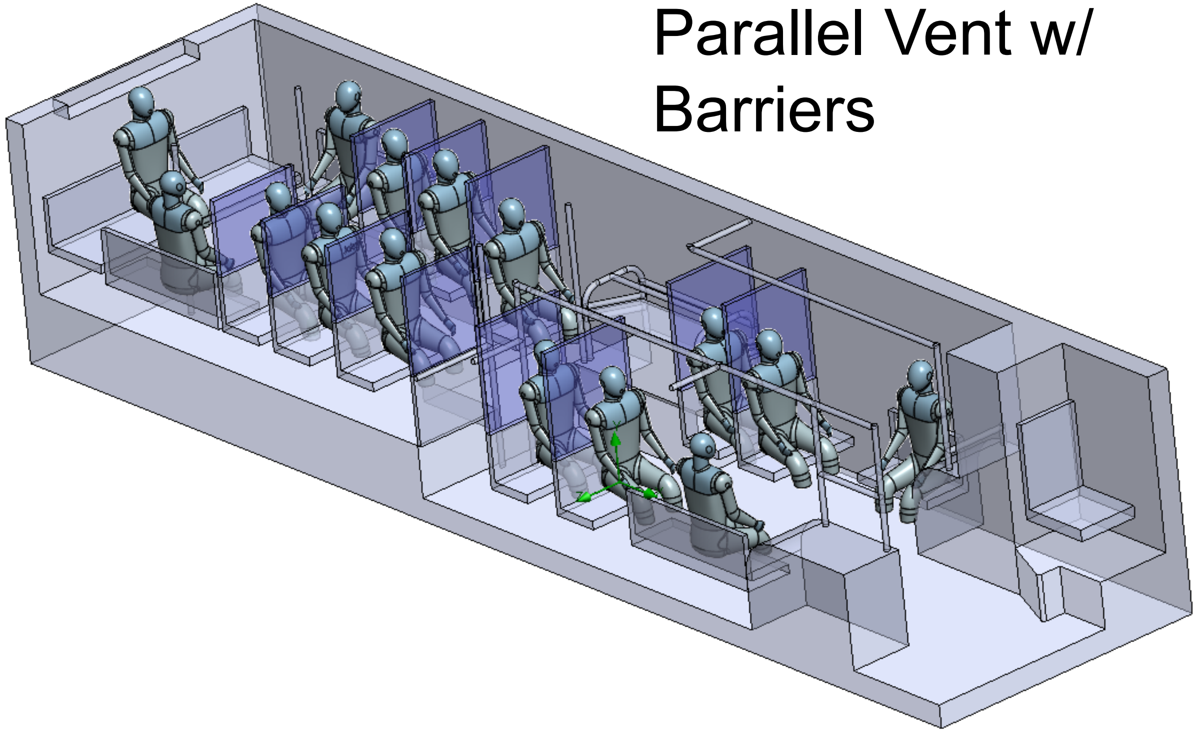
- Both configurations with and without thermal plume effect
- Both configurations with the coughing dummy in front and rear of bus

CFD configurations

Parallel Vent System



Parallel Vent w/
Barriers

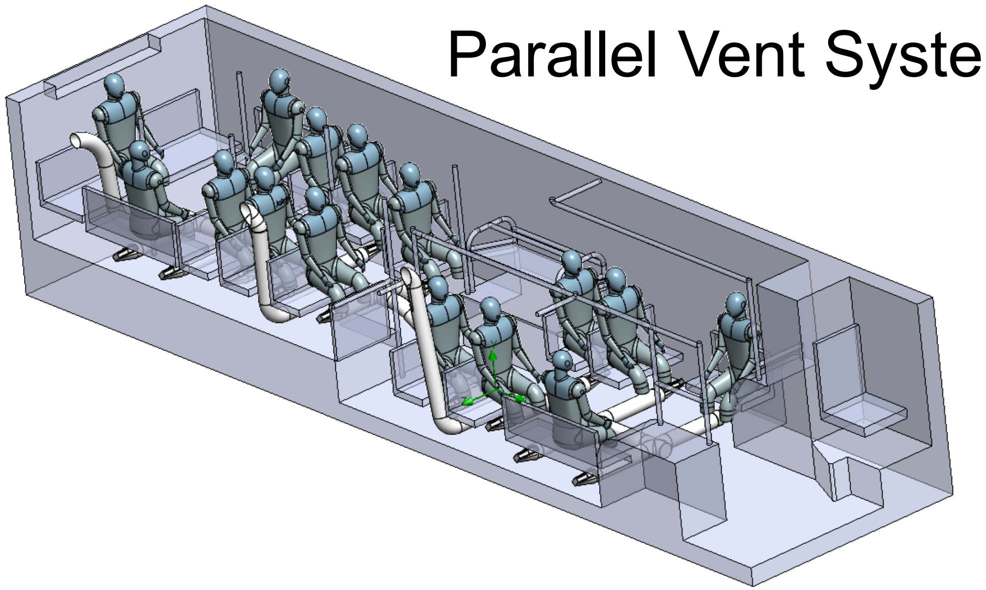


- Flow goes from the top to the bottom of the vent system
- Both configurations with and without thermal plume effect
- Both configurations with the coughing dummy in front and rear of bus

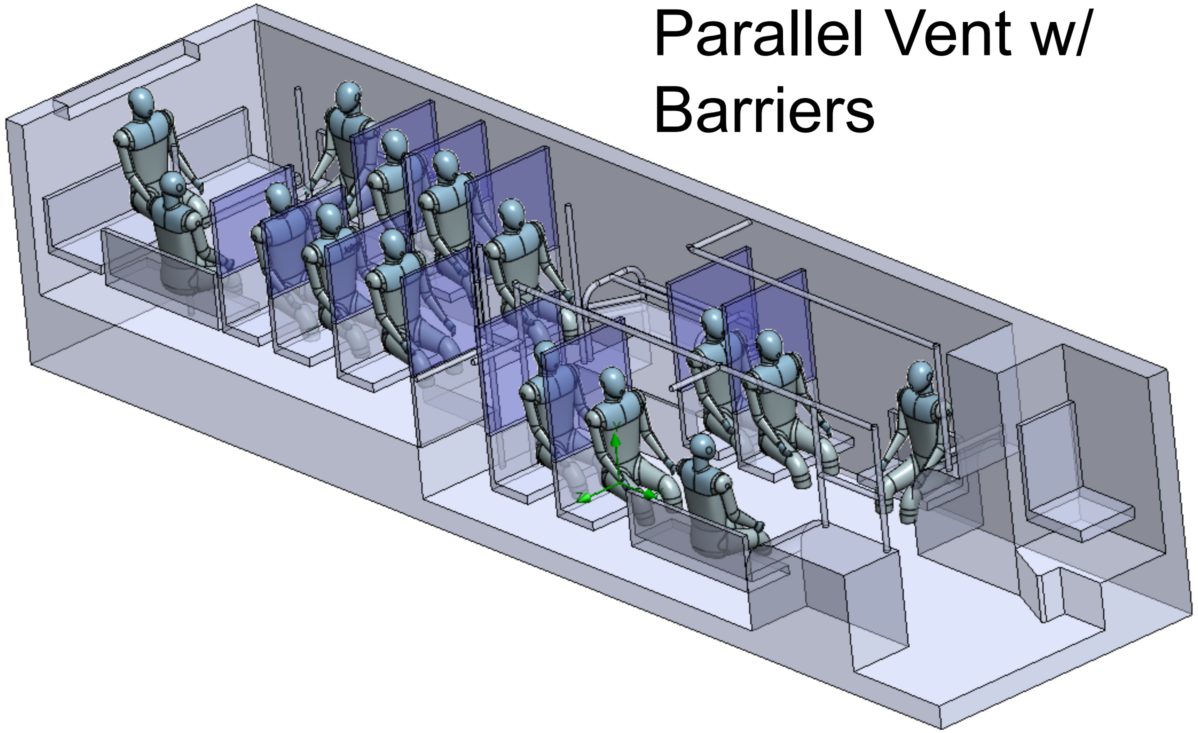
Flow

CFD configurations

Parallel Vent System



Parallel Vent w/ Barriers



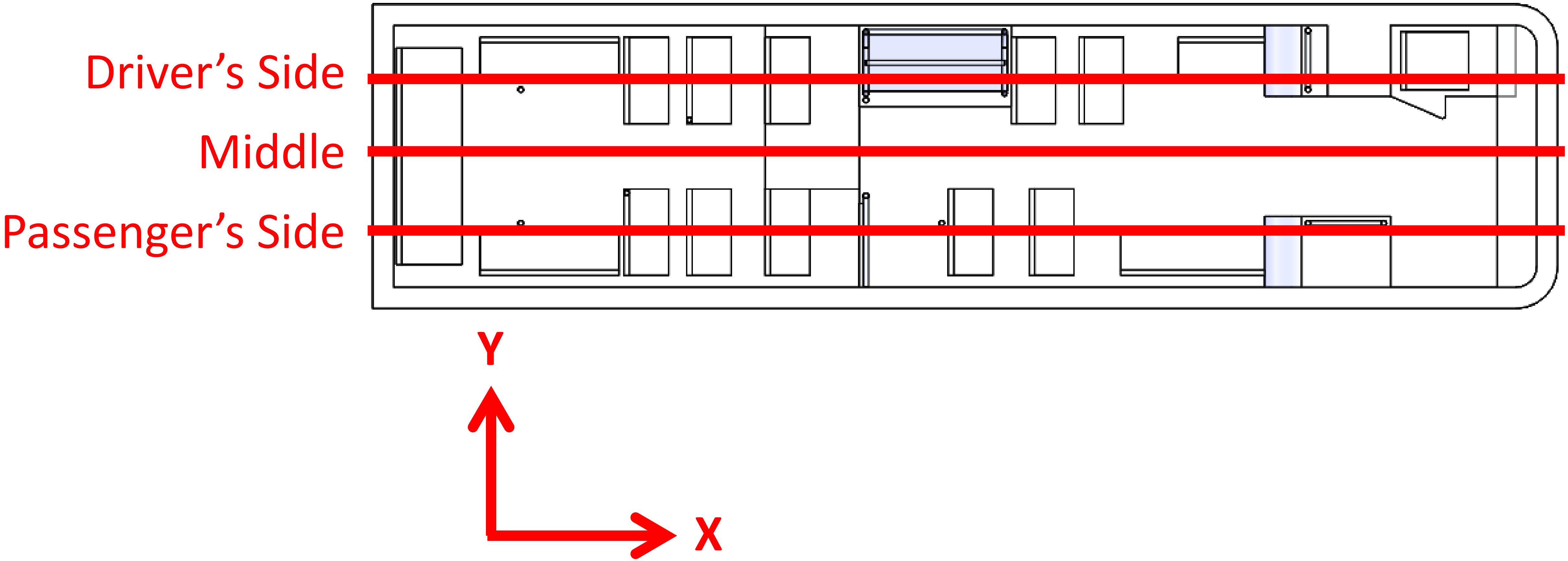
- Flow goes from the bottom to the top of the vent system
- Both configurations with and without thermal plume effect
- Both configurations with the coughing dummy in front and rear of bus

Flow

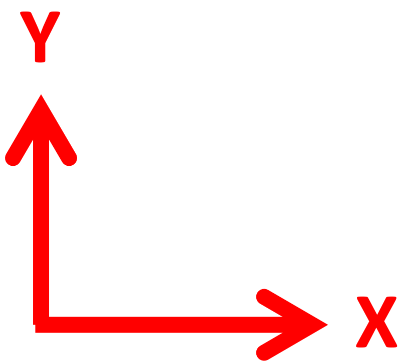
Test matrix for CFD studies

Case #	Vent Configuration	Flow Direction	Barriers	Coughing position	Thermal Plume
1	Baseline	Down	N	Front	N
2					Y
3				Rear	N
4					Y
5			Y	Front	N
6					Y
7				Rear	N
8					Y
9	Parallel flow	Down	N	Front	N
10					Y
11				Rear	N
12					Y
13			Y	Front	N
14					Y
15				Rear	N
16					Y
17		Up	N	Front	N
18					Y
19				Rear	N
20					Y
21			Y	Front	N
22					Y
23				Rear	N
24					Y

Velocity Contour Plot Locations



CFD Results – Baseline Bus Configuration (Cases 1 & 3)

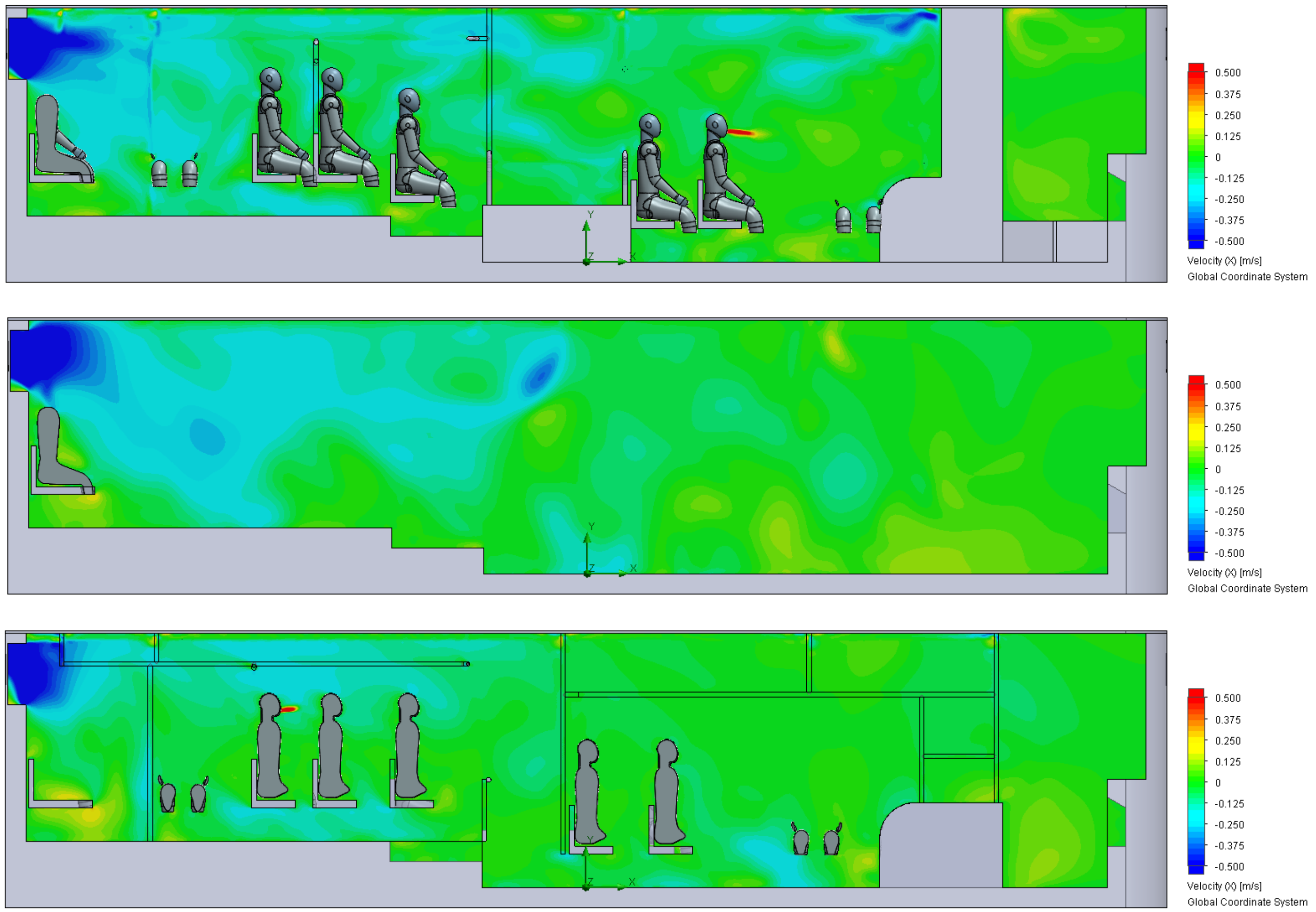


Driver's Side

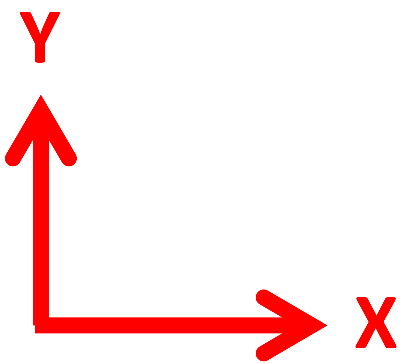
Middle

Passenger's Side

{X-Velocity plots}



CFD Results – Parallel Vent w/o Barriers Configuration (Downflow) (Cases 9 & 11)

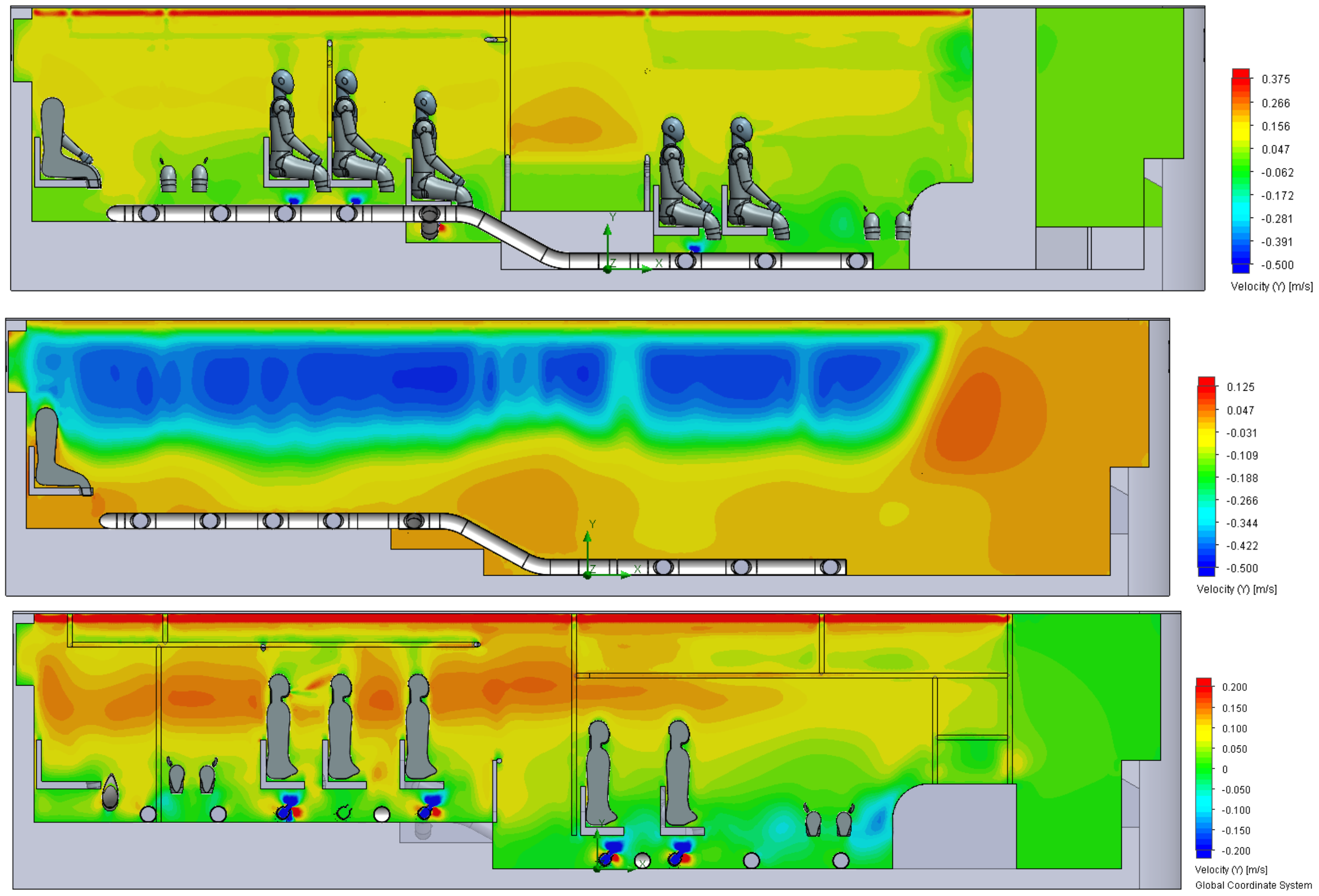


{Y-Velocity plots}

Driver's Side

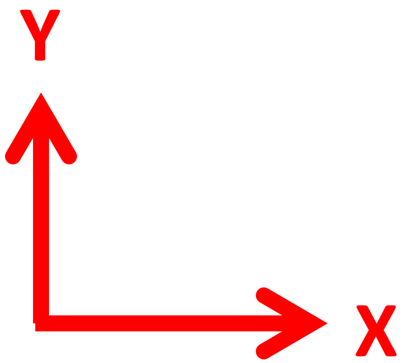
Middle

Passenger's Side



CFD Results – Parallel Vent w/ Barriers Configuration (Upflow & Thermal Plume) (Cases 22 & 24)

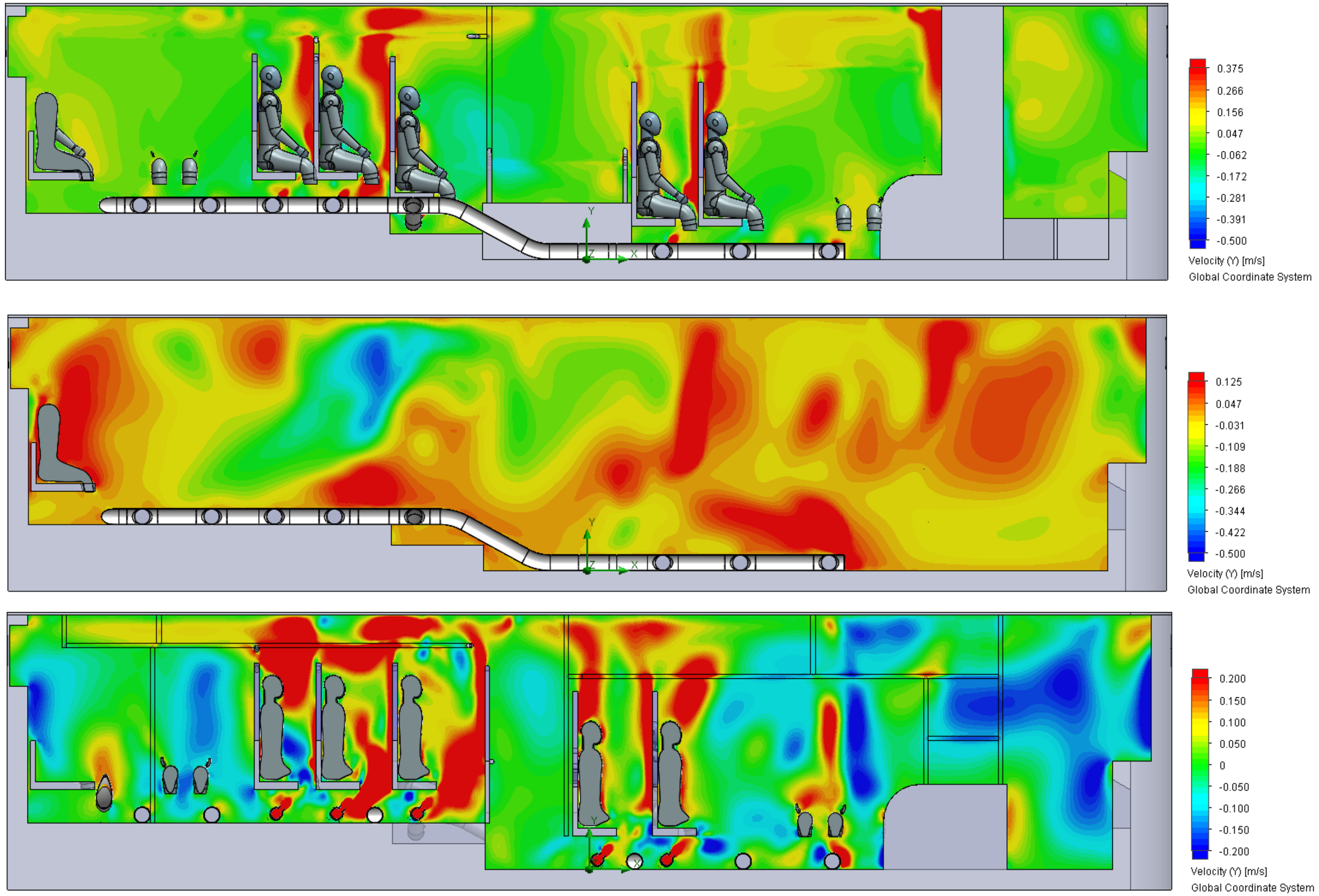
{Y-Velocity plots}



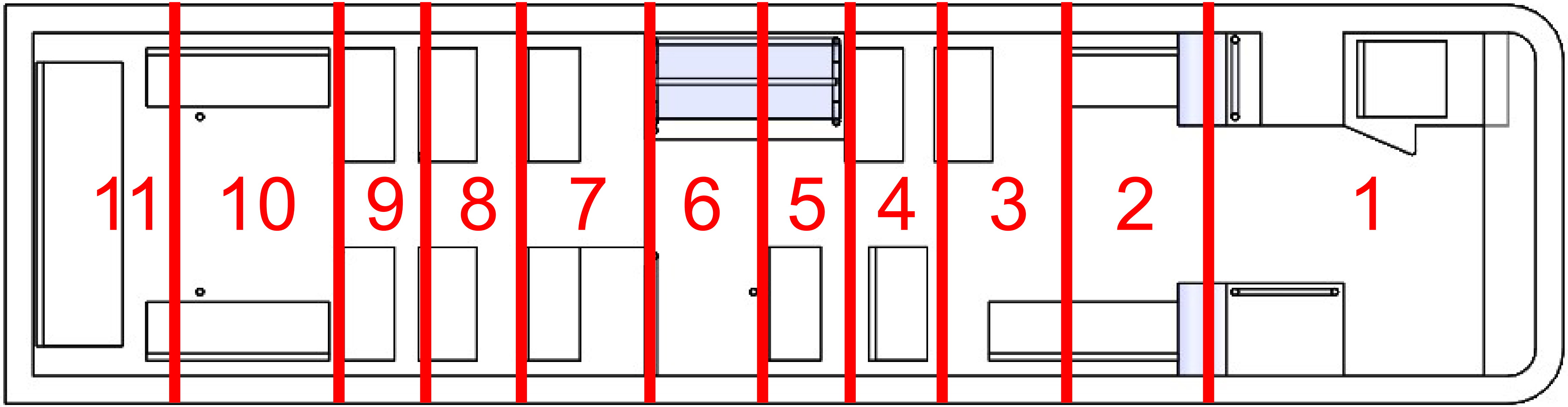
Driver's Side

Middle

Passenger's Side

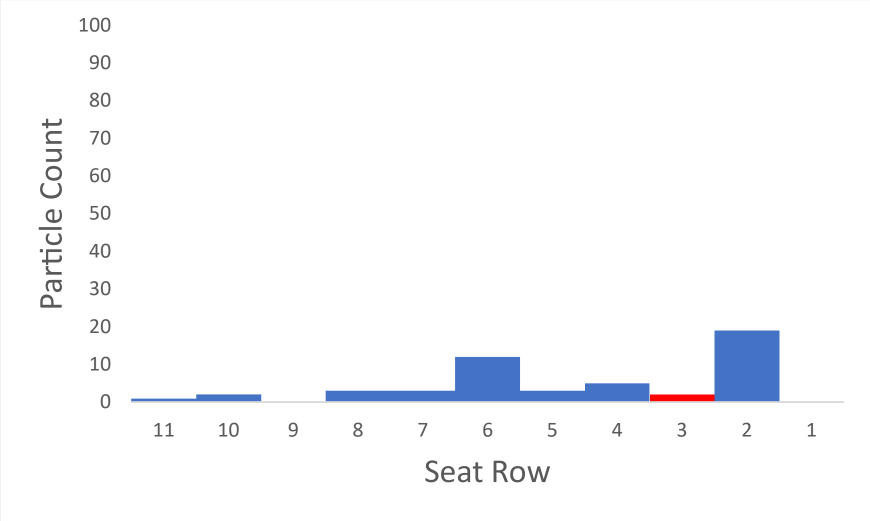


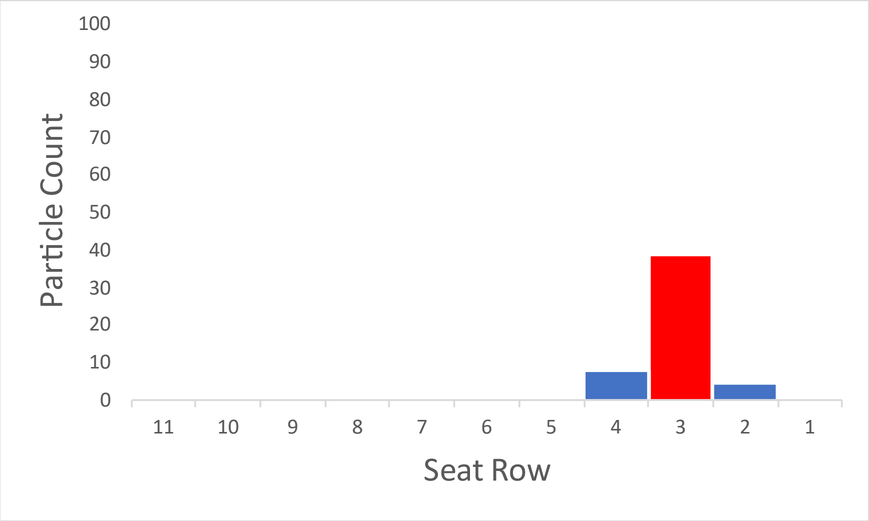
Bus Row/Bin Width Divisions for particle trajectory simulations



Seat row numbering

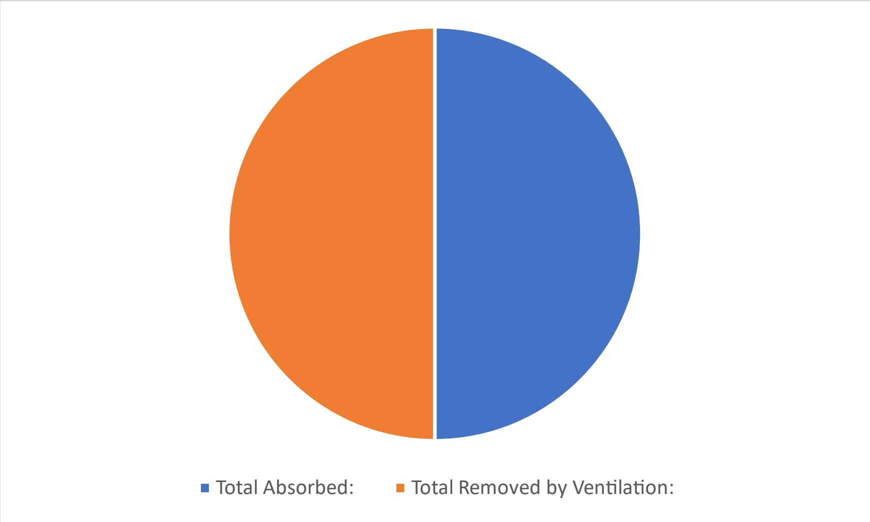
Baseline vs Parallel Vent: Front, Downflow, No Barriers, No Thermal Plume (1 vs 13)

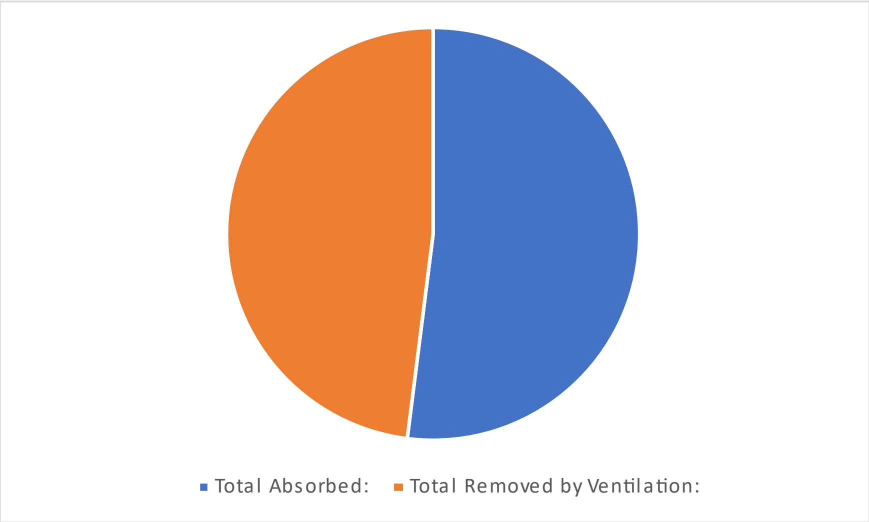




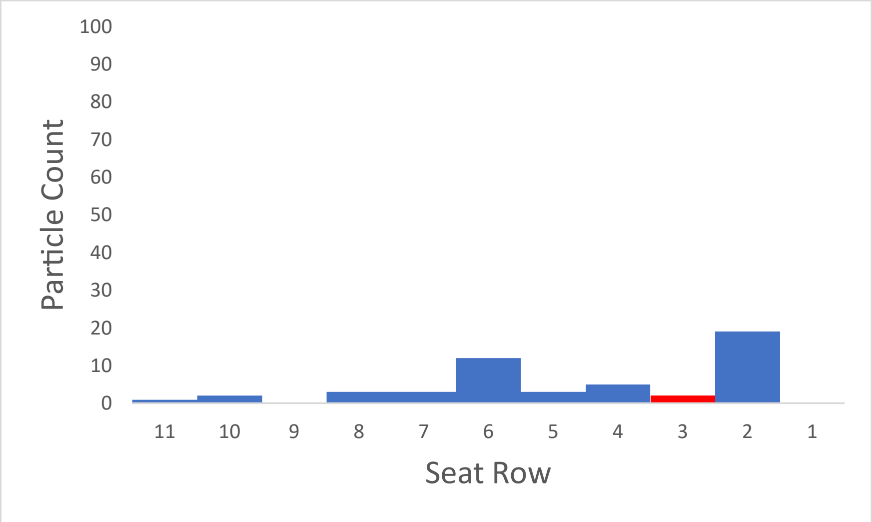
Baseline

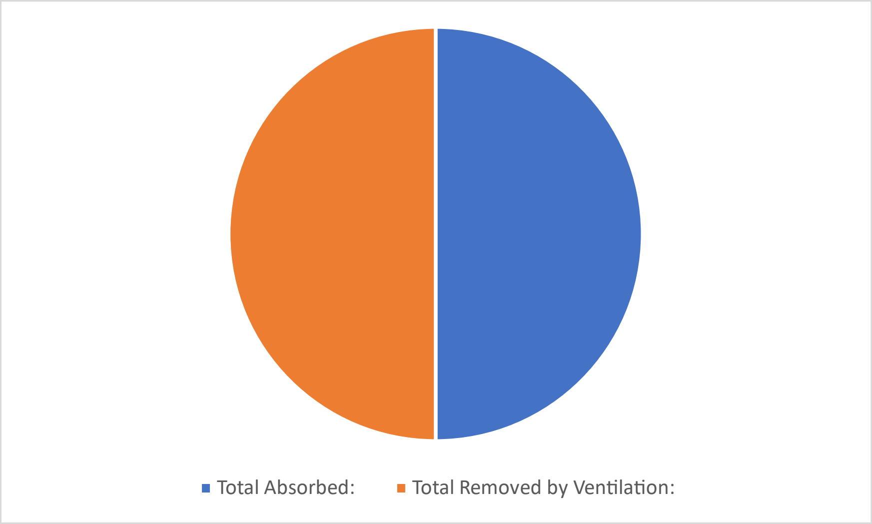
Parallel Vent





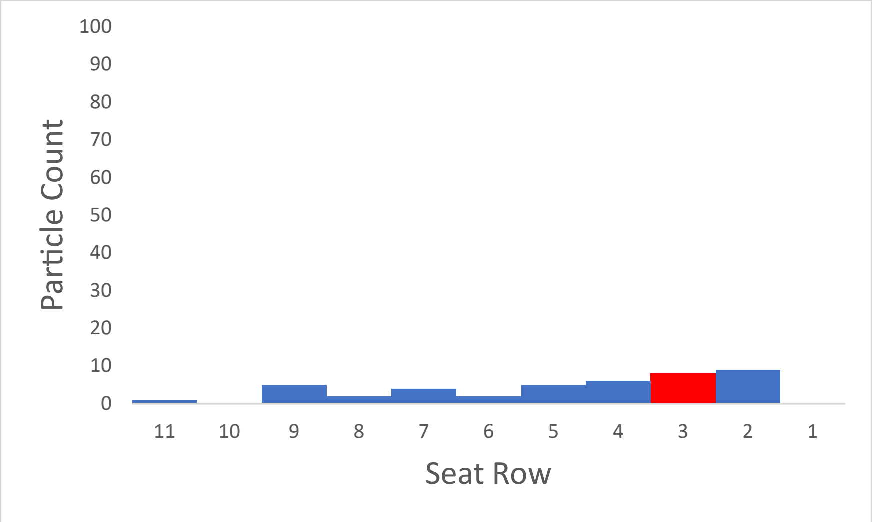
Barriers vs No Barriers: Baseline, Front, Downflow, No Thermal Plume (1 vs 5)

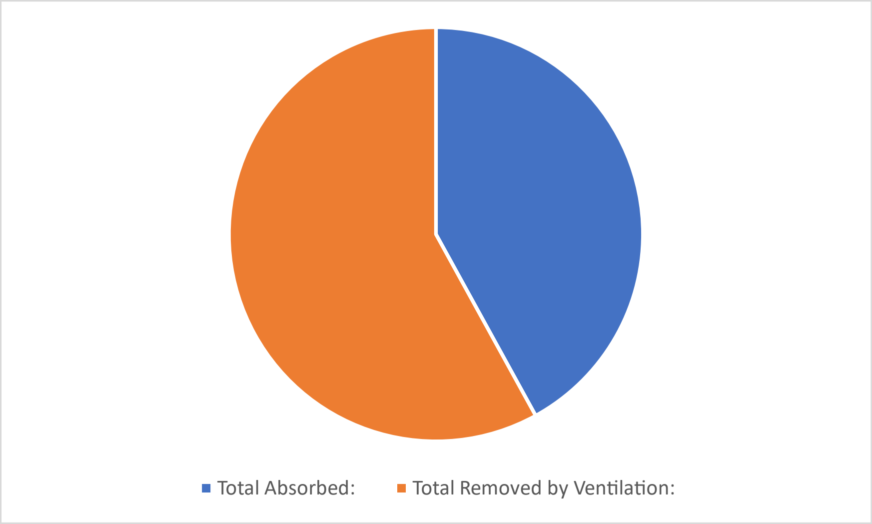




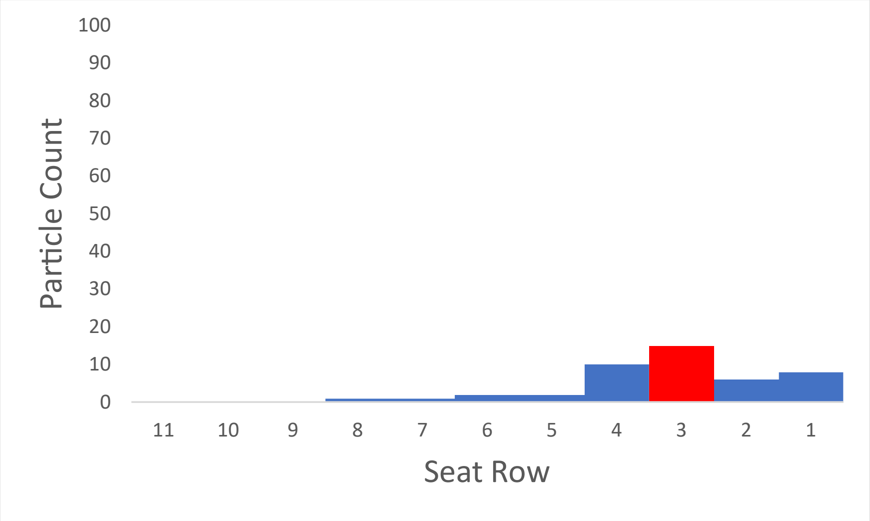
Barriers

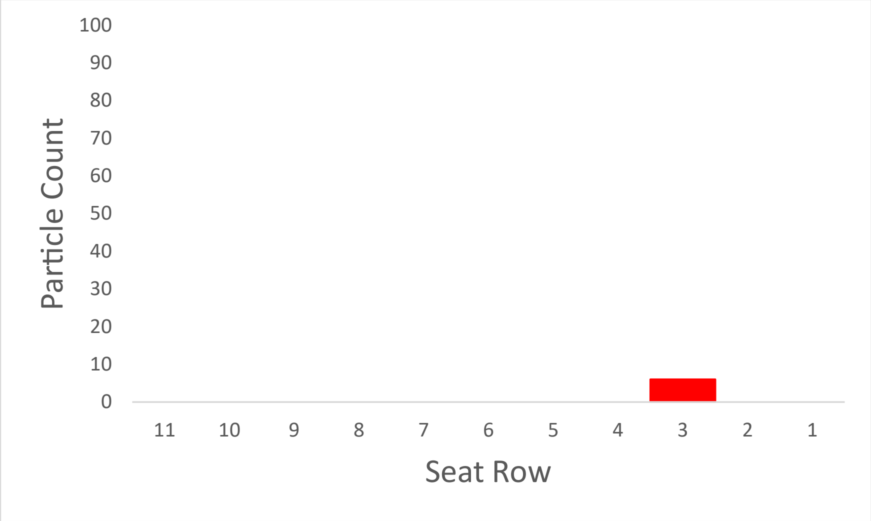
No Barriers





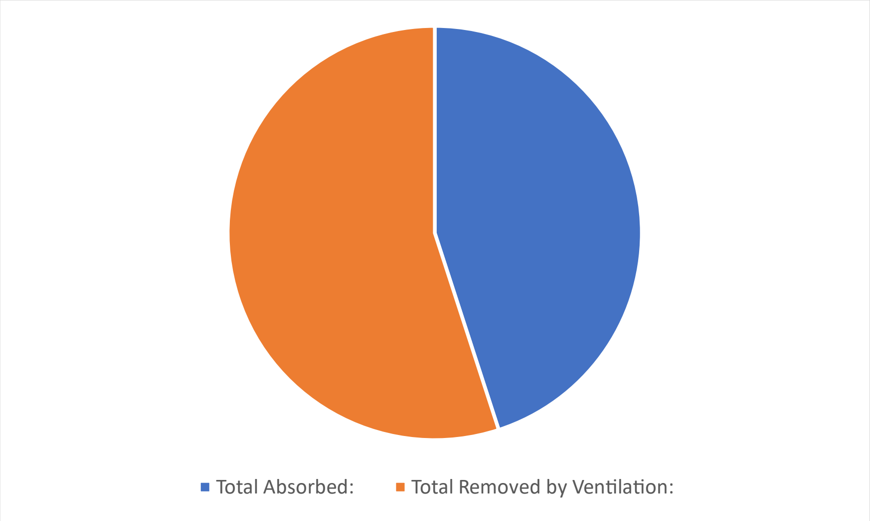
Thermal Plume vs No Thermal Plume: Parallel Vent, Front, Upflow, Barriers (21 vs 22)

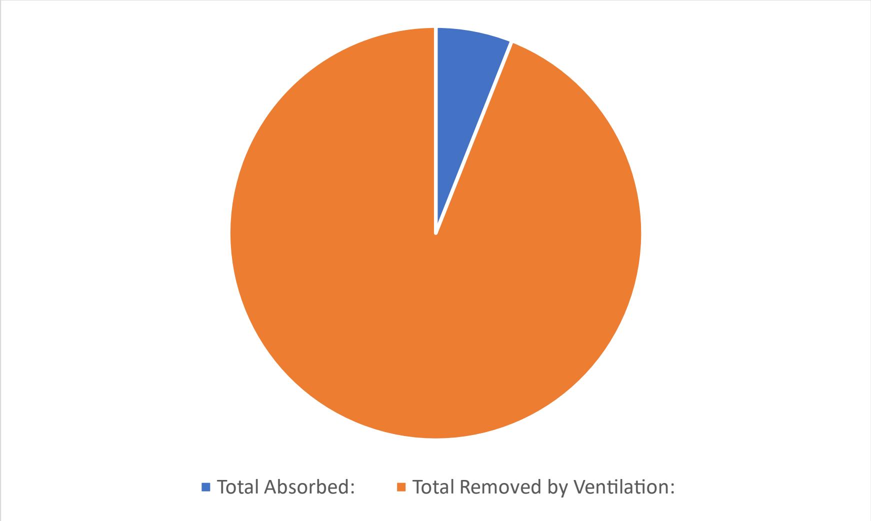




No Thermal Plume

Thermal Plume





Case #	Vent Configuration	Flow Direction	Barriers	Coughing position	Thermal Plume
1	Baseline	Down	N	Front	N
2					Y
3				Rear	N
4					Y
5			Y	Front	N
6					Y
7				Rear	N
8					Y
9	Parallel flow	Down	N	Front	N
10					Y
11				Rear	N
12					Y
13			Y	Front	N
14					Y
15				Rear	N
16					Y
17		Up	N	Front	N
18					Y
19				Rear	N
20					Y
21			Y	Front	N
22					Y
23				Rear	N
24					Y

Summary result:

In baseline system, regardless of where the “coughing” subject is, the effect of the thermal plume on dispersion of particles to other parts of the bus is minimal

More “dispersion” = increased risk of infection

Case #	Vent Configuration	Flow Direction	Barriers	Coughing position	Thermal Plume
1	Baseline	Down	N	Front	N
2					Y
3				Rear	N
4					Y
5			Y	Front	N
6					Y
7				Rear	N
8					Y
9	Parallel flow	Down	N	Front	N
10					Y
11				Rear	N
12					Y
13			Y	Front	N
14					Y
15				Rear	N
16					Y
17		Up	N	Front	N
18					Y
19				Rear	N
20					Y
21			Y	Front	N
22					Y
23				Rear	N
24					Y

Summary result:

Regardless of where the "coughing" subject is – Parallel system is a benefit – reduces the dispersion of particles to other parts of the bus

Case #	Vent Configuration	Flow Direction	Barriers	Coughing position	Thermal Plume
1	Baseline	Down	N	Front	N
2					Y
3				Rear	N
4					Y
5			Y	Front	N
6					Y
7				Rear	N
8					Y
9	Parallel flow	Down	N	Front	N
10					Y
11				Rear	N
12					Y
13			Y	Front	N
14					Y
15				Rear	N
16					Y
17		Up	N	Front	N
18					Y
19				Rear	N
20					Y
21			Y	Front	N
22					Y
23				Rear	N
24					Y

Summary result:

In baseline system, regardless of where the "coughing" subject is, the effect of barriers on dispersion of particles to other parts of the bus is minimal – most particles still flow out the back vent

Case #	Vent Configuration	Flow Direction	Barriers	Coughing position	Thermal Plume
1	Baseline	Down	N	Front	N
2					Y
3				Rear	N
4					Y
5			Y	Front	N
6					Y
7				Rear	N
8					Y
9	Parallel flow	Down	N	Front	N
10					Y
11				Rear	N
12					Y
13			Y	Front	N
14					Y
15				Rear	N
16					Y
17		Up	N	Front	N
18					Y
19				Rear	N
20					Y
21			Y	Front	N
22					Y
23				Rear	N
24					Y

Summary result:

With the particle generator in the front and the rear and the Parallel system, the barriers are a benefit – reduces the dispersion of particles to other parts of the bus

Case #	Vent Configuration	Flow Direction	Barriers	Coughing position	Thermal Plume
1	Baseline	Down	N	Front	N
2					Y
3				Rear	N
4					Y
5			Y	Front	N
6					Y
7				Rear	N
8					Y
9	Parallel flow	Down	N	Front	N
10					Y
11				Rear	N
12					Y
13			Y	Front	N
14					Y
15				Rear	N
16					Y
17		Up	N	Front	N
18					Y
19				Rear	N
20					Y
21			Y	Front	N
22					Y
23				Rear	N
24					Y

Summary result:

With the generator in the front and the back in the upflow condition, the addition of the “thermal plume” – it appears the dispersion of particles to other parts of the bus is reduced

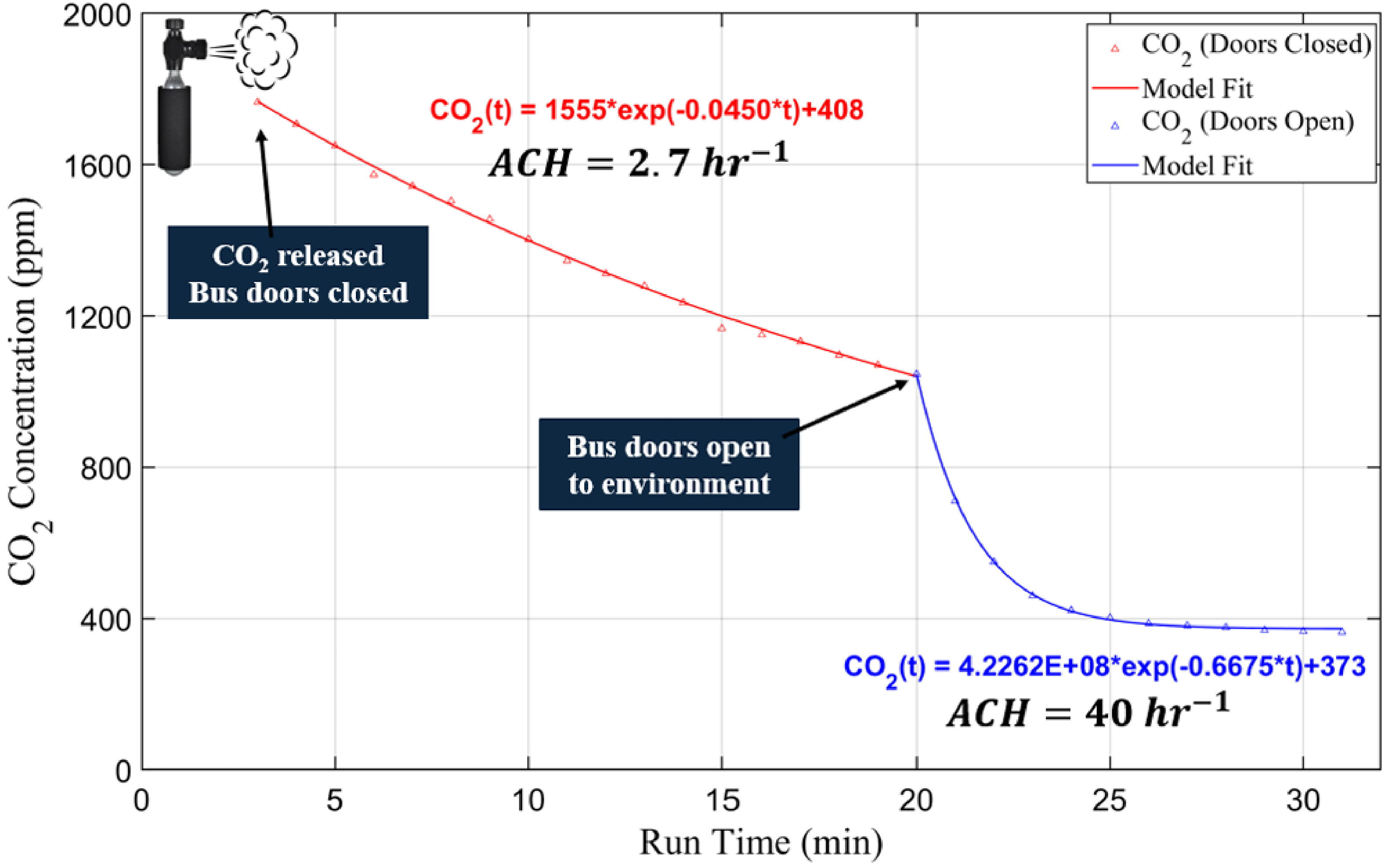
Case #	Vent Configuration	Flow Direction	Barriers	Coughing position	Thermal Plume
1	Baseline	Down	N	Front	N
2					Y
3				Rear	N
4					Y
5			Y	Front	N
6					Y
7				Rear	N
8					Y
9	Parallel flow	Down	N	Front	N
10					Y
11				Rear	N
12					Y
13			Y	Front	N
14					Y
15				Rear	N
16					Y
17		Up	N	Front	N
18					Y
19				Rear	N
20					Y
21			Y	Front	N
22					Y
23				Rear	N
24					Y

Summary result:

With the generator in the front and the rear, it appears the particles disperse to other areas much more in the downflow case than the upflow case

Experimental Results

Air Change per Hour (ACH, $hour^{-1}$)



$$C_{cabin}(t) = (A - B)\exp(-Ct) + B \quad \textbf{Eqn 1}$$

$$C = \frac{1}{\tau} * 60 \quad \textbf{Eqn 2}$$

We curve fit data from 10 sensors individually to determine ACH and average and determine standard deviations

Air Change per Hour (ACH, $hour^{-1}$), stationary test

Bus A

A/C fan	Hi	Hi	Hi	Hi
Driver fan	off	off	off	off
Door	Doors closed	Front Door Open	Rear Door Open	Doors open
ACH (h^{-1})	2	12	13	37

Bus B

A/C fan	Hi	Hi	Hi	Hi
Driver fan	off	Lo	Hi	off
Door	Doors closed	Doors closed	Doors closed	Front door open
ACH (h^{-1})	0.7	4.6	6.3	5.3

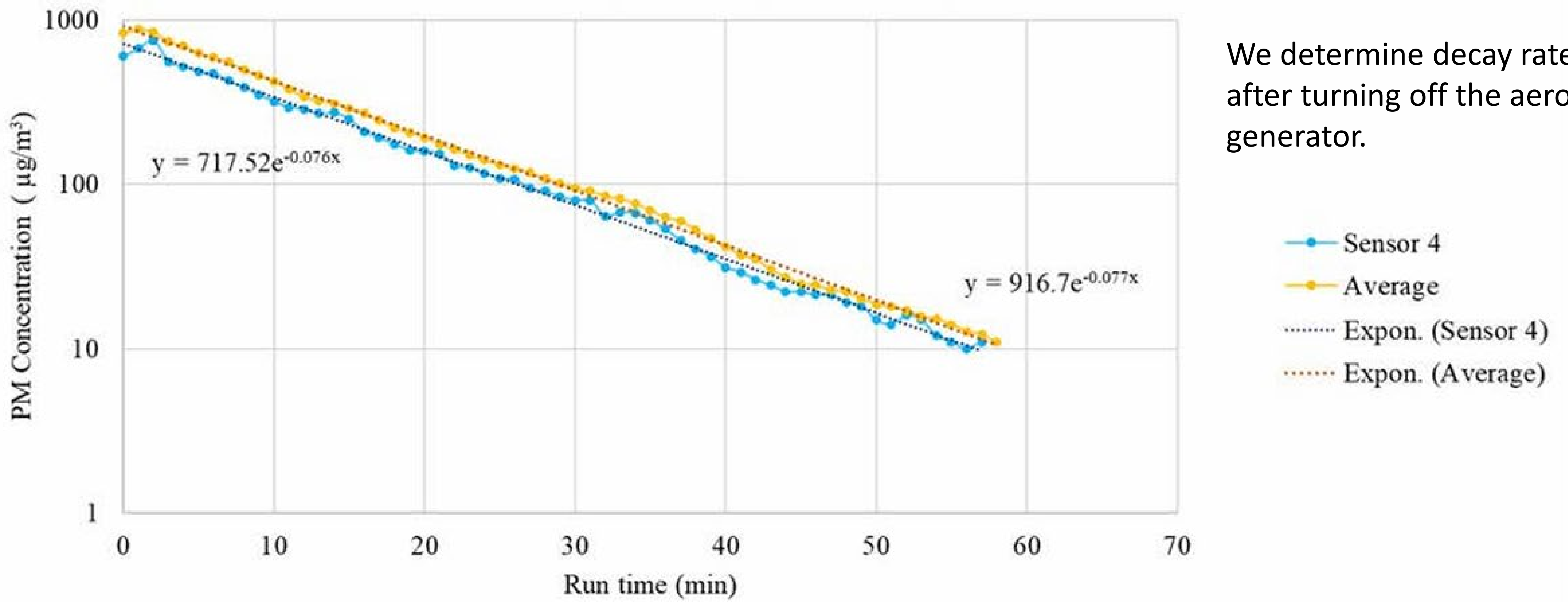
Air Change per Hour (ACH, $hour^{-1}$), on-road test

Bus B

A/C fan	Hi	Hi	Hi
Driver fan	Hi	off	off
Door	Doors closed	Doors closed	Stop-and-Go
ACH (h^{-1})	8	8	27

Stop-and-Go condition: 6 laps around the testing pathway, with full stops of 20-40 s at the end of each lap that simulate passenger loading and unloading with both doors opening and closing.

PM removal rate, eACH (hour^{-1})



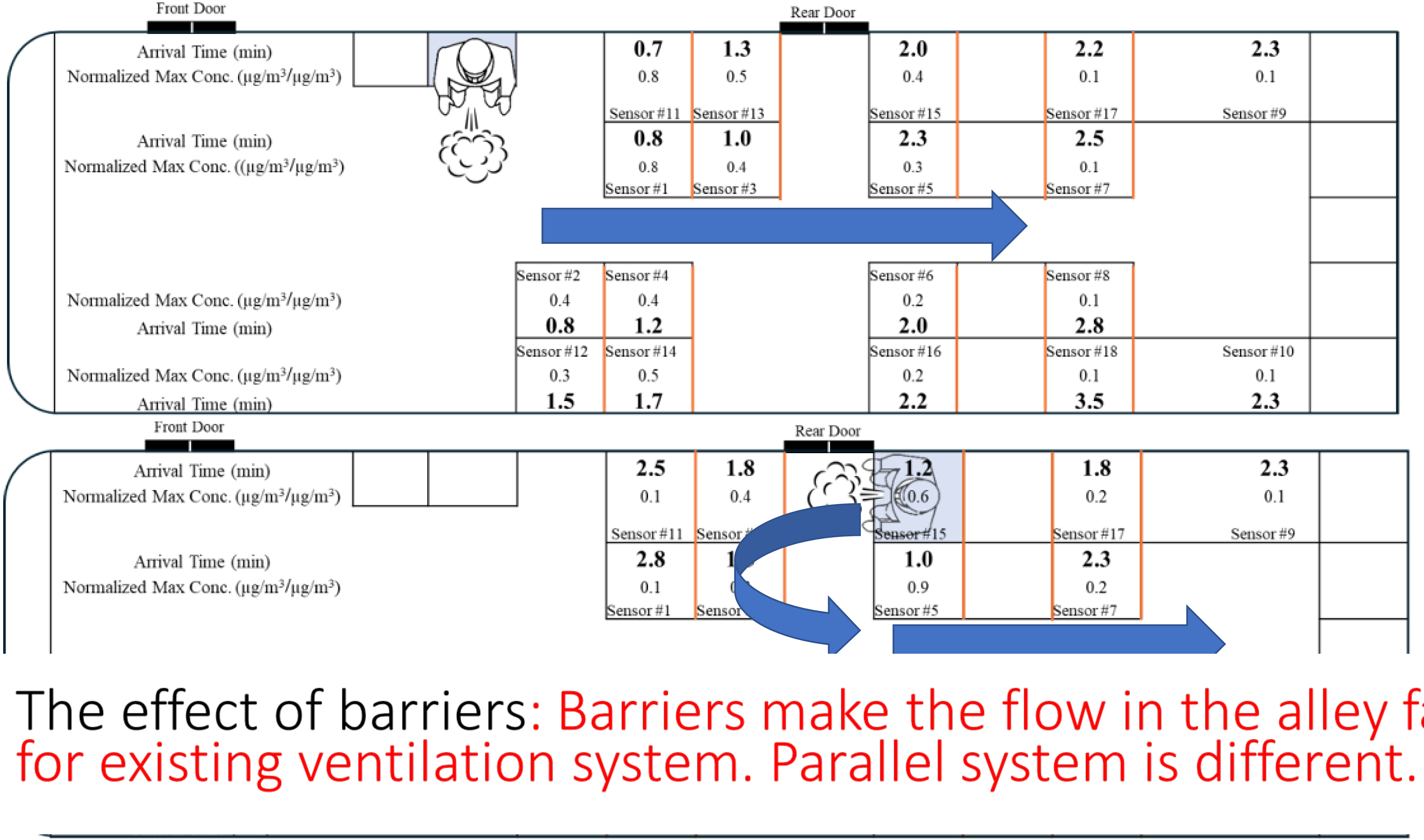
We determine decay rate of particles after turning off the aerosol generator.

PM removal rate, eACH ($hour^{-1}$)

Separate air cleaners are very effective

Bus#2				
Experimental Condition	Baseline	Baseline	HEPA air purifiers	HEPA air purifiers
AC Fan	Off	Hi	Hi	Hi
Driver Fan	Off	Off	Off	Off
Aerosol Generator Location	Front Seat	Front Seat	Middle Seat	Front Seat
eACH (h^{-1})	5	10	23	21

Particle arrival time analysis



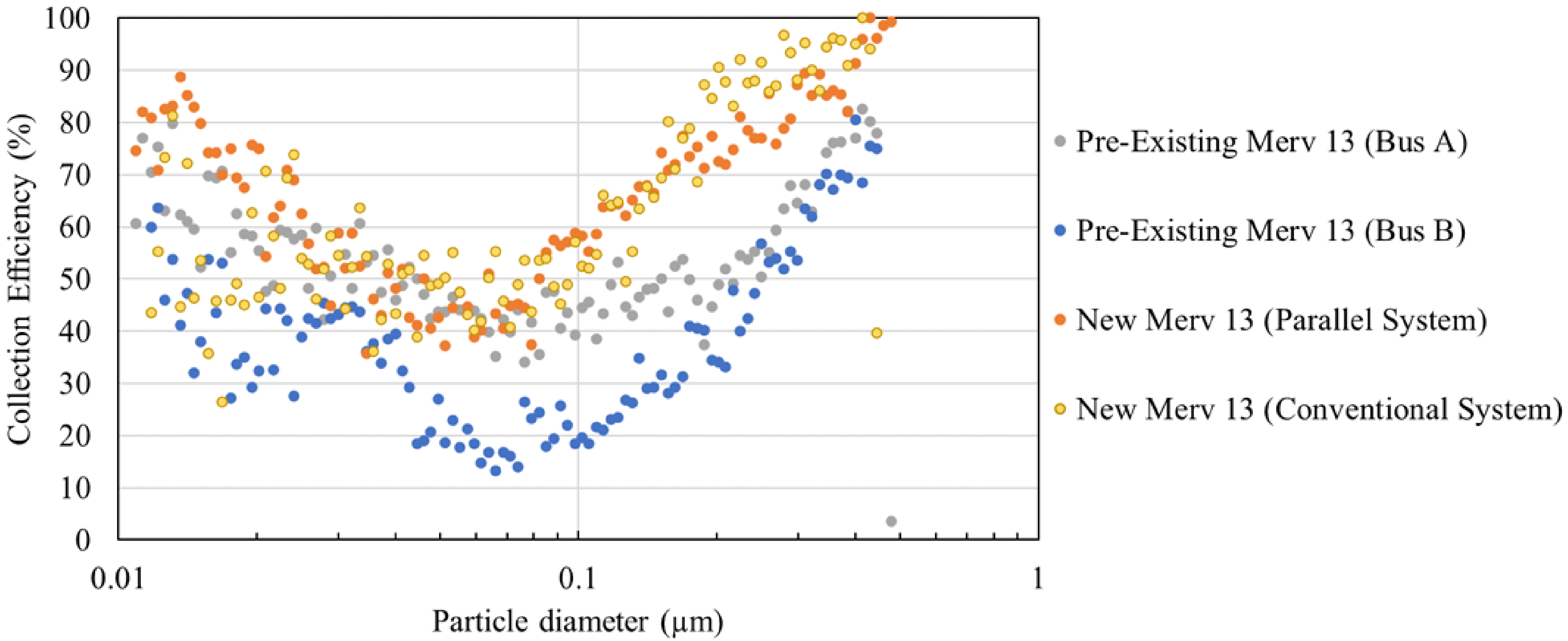
The effect of barriers: Barriers make the flow in the alley faster for existing ventilation system. Parallel system is different.


Front Door
Rear Door
Arrival Time (min)
Normalized Max Conc. (μg/m³/μg/m³)
3.0
0.0
Sensor #11
2.7
0.1
Sensor #13
2.2
0.2
Sensor #15
0.8
0.6
Sensor #17
0.8
1.0
Arrival Time (min)
Normalized Max Conc. (μg/m³/μg/m³)
3.3
0.1
Sensor #1
2.7
0.0
Sensor #3
2.2
0.2
Sensor #5
0.8
0.5
Sensor #7
Sensor #2
0.1
3.0
Sensor #4
0.1
3.0
Sensor #6
0.2
2.0
Sensor #8
0.5
0.8
Normalized Max Conc. (μg/m³/μg/m³)
Arrival Time (min)
Sensor #12
0.0
3.3
Sensor #14
0.1
3.5
Sensor #16
0.2
2.2
Sensor #18
0.6
2.0
1.4
0.5
Normalized Max Conc. (μg/m³/μg/m³)
Arrival Time (min)

Summary table

	Arrival time range (min)			eACH (hr^{-1})			Normalized max concentrations (near vs away)					
AG location	*Front*	*Middle*	*Back*	*Front*	*Middle*	*Back*	*Front*		*Middle*		*Back*	
Conventional System	2-3	1-5	3-4	9.2	-	-	1.0 - 0.9	1.0 - 0.6	1.1 - 0.8	0.9 - 0.6	0.5 - 0.4	0.7 - 0.4
Conventional System + Barriers	2-3	2-3	2-3	12	11	13	1.1 - 0.9	0.9 - 0.4	0.8 - 0.7	0.6 -0.3	0.5 - 0.4	0.7 - 0.3
Baseline Parallel System	0.3-2	0.3-1.8	0.7-2.5	42	44	42	1.5 - 0.6	1.0 -0.1	0.4	0.9 - 0.2	1.2 - 0.8	0.5 - 0.1
Parallel System + Barriers	0.3-2.5	0-1.3	0.3-2.5	36	41	37	1.2 - 0.5	0.6 - 0.1	1.4 - 0.6	0.3 - 0.1	0.6 - 0.4	0.3 - 0.1
Air shower parallel + Barriers	0.8-2.8	1-2.8	0.5-3.3	37	37	37	0.8 - 0.4	0.4 - 0.1	1.2 - 0.9	0.3 - 0.1	1.4 - 1.0	0.5 - 0

The effect of new filter



Other content in our final report

- **Extension of results to alternative modes of transportation**
  - Modeling parallel flow ventilation system in other modes of transportation (subway carriage and tram car)
  - Showing how a “closed box model” can be used to optimize space to reduce virus transmission
    - COVID-19 Aerosol Transmission Estimator tool developed by Jimenez and Peng. https://tinyurl.com/covid-estimator

Recommendations and conclusions

- Replace the in-use air filters with new MERV 13 cabin filters immediately when an event like an airborne virus outbreak occurs.

- Install stand-alone HEPA purifiers along with the equipped HVAC system is an effective method for removing viruses in the air. conditions. However, stand-alone HEPA air purifiers are not suitable under nonemergency conditions.

- The effects of barriers are minimal when a conventional ventilation system is used. However, barriers can augment the effectiveness of a parallel flow ventilation system. The research does not support the installation of barriers as a retrofit solution.

- The parallel flow ventilation system is much more effective in removing airborne viruses than the conventional bus ventilation system. (An engineering solution!)

Thanks!

Q&A

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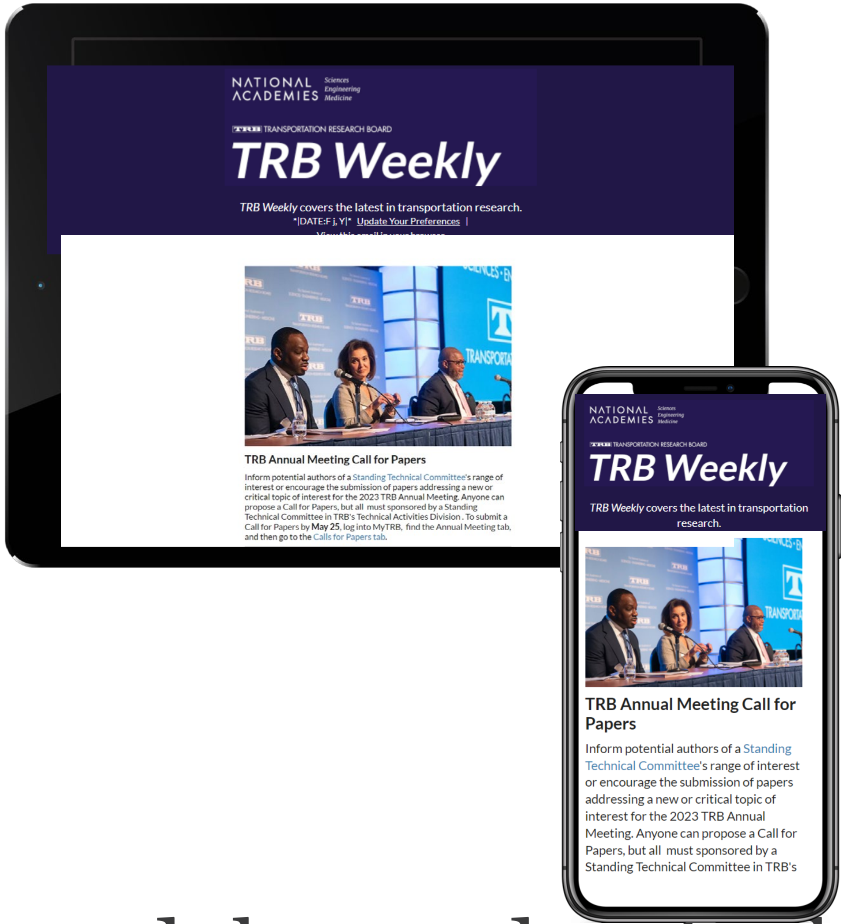

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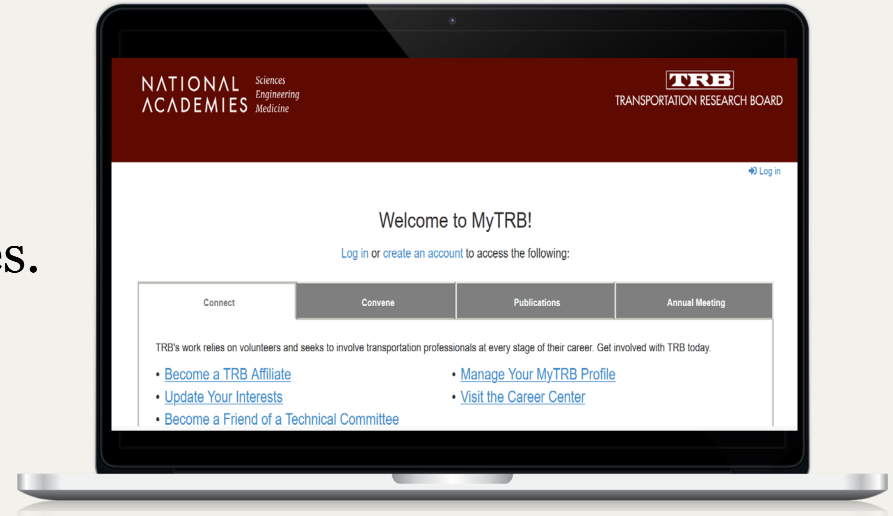

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