**Risk of SARS-CoV-2 in a car cabin assessed through 3D CFD simulations**

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**Abstract**
In this study, the risk of infection from SARS-CoV-2 Delta variant of passengers sharing a car cabin with an infected subject for a 30-min journey is estimated through an integrated approach combining a recently developed predictive emission-to-risk approach and a validated CFD numerical model numerically solved using the open-source OpenFOAM software. Different scenarios were investigated to evaluate the effect of the infected subject position within the car cabin, the airflow rate of the HVAC system, the HVAC ventilation mode, and the expiratory activity (breathing vs. speaking). The numerical simulations here performed reveal that the risk of infection is strongly influenced by several key parameters: As an example, under the same ventilation mode and emitting scenario, the risk of infection ranges from zero to roughly 50% as a function of the HVAC flow rate. The results obtained also demonstrate that (i) simplified zero-dimensional approaches limit proper evaluation of the risk in such confined spaces, conversely, (ii) CFD approaches are needed to investigate the complex fluid dynamics in similar indoor environments, and, thus, (iii) the risk of infection in indoor environments characterized by fixed seats can be in principle controlled by properly designing the flow patterns of the environment.

**KEYWORDS**
car cabin, CFD analysis, respiratory particles, risk of infection, SARS-CoV-2, virus transmission

**1 | INTRODUCTION**

Transport microenvironments are confined spaces of concern in terms of SARS-CoV-2 risk of infection due to the high crowding indexes (number of people relative to the size of the confined space) and the possible inadequate clean (pathogen-free) air supply. Indeed, a number of outbreaks occurred worldwide in buses, airplanes, and ships. These outbreaks are mainly due to the airborne transmission of inhalable virus-laden airborne respiratory particles (i.e., particles below 100 μm in diameter), which are capable of remaining suspended in the air then likely infecting simultaneously numerous susceptible subjects that share the same confined space of the infected subject. This route of transmission was accepted as the main pathway of infection transmission only in the spring 2021 when, faced with the accumulating scientific evidence, both US CDC and WHO released updated guidelines reporting the negligible role of the spray borne particles (larger particles >100 μm quickly settling due to their inertia) and fomites (i.e., contaminated surfaces) with respect to the airborne respiratory particles (WHO, April 30th, 2021; US CDC, May 7th, 2021). Indeed, SARS-CoV-2 virus has been detected in airborne samples collected in indoor environments such as hospital microenvironments (where certain presence...
of infected subjects allows simpler particle samplings) but also in transport microenvironments, including passenger cars. Thus, despite the implementation of spray borne and surface touch mitigation strategies (i.e., wearing cloth or surgical masks, and washing hands), whose effectiveness on airborne respiratory particles is questionable, reducing the airborne SARS-CoV-2 concentration in such environments is essential in view of reducing the risk of infection of susceptible people exposed. To this end, providing appropriate pathogen-free air supply rates (i.e., air exchange rates) represent a key approach in view of reducing the airborne SARS-CoV-2 concentration in those environments. Beyond increased dilution, improved ventilation strategies (e.g., personal and displacement) are also needed that can more effectively remove airborne contaminants from the breathing zone, instead of simply dispersing particles throughout the room. Although public transport microenvironments (trains, airplanes, and buses) could provide, at least in principle, air exchange rates defined by technical standards (e.g., as a function of the occupancy), the ventilation rates in private cars are set by the passengers according to their air quality/thermal comfort perception rather than contaminant removal concerns. Indeed, an epidemiological study, recently carried out in Singapore in order to explore the transmission risk factors for COVID-19, recognized a significant risk of transmission among non-household contacts sharing a vehicle with an infected subject.

A priori estimates of the risk of infection in cars can be carried out adopting prospective assessments based on a known/estimated emission of virus-laden particles and then diluting them in the indoor environment through either simplified zero-dimensional approaches or complex 3D transient approaches. Zero-dimensional approaches are based on the simplified hypothesis of complete and instantaneous mixing of the emission to achieve a uniform spatial concentration within the environment; they represent a practical solution to easily obtain rough estimates of concentrations and risks when site-specific information regarding the ventilation, geometry, position of the source, etc. are not available. Nonetheless, perfectly mixed conditions (hereinafter referred to as “well-mixed”) are unlikely in spaces with high ventilation rates, thus, such hypothesis is even less accurate for large indoor environments characterized by reduced mixing or small confined spaces, as car cabins, where the position of inlet air vents of the HVAC system, the airflow rate entering the car cabin, the air recirculation and its filtration can significantly affect the airflow in the cabin, and then the exposure and risk of passengers.

Indeed, even if the average air exchange rate in car cabin can be quite high (e.g., >100 h⁻¹ when high fan speeds are set or windows are kept open), stagnation regions can occur as a result of the specific airflows pattern across the cabin itself. Therefore, for these environments the average risk evaluated through well-mixed models could overestimate or underestimate the actual risk of some of the passengers in the car.

For these reasons, computational fluid dynamics (CFD) represent an essential approach to investigate the risk of infection in car cabins as it provides detailed information about spatial and temporal virus-laden particle distribution, as a function of specific boundary conditions and ventilation scenarios, by solving the well-known mass, momentum, and energy conservation equations alongside with a proper turbulence model. To this end, in our previous study we investigated the particle dispersion in a car cabin through an Eulerian-Lagrangian approach able to perform transient non-isothermal numerical analyses. Such an approach was also experimentally validated against PIV measurements available in the scientific literature then providing a validated and suitable approach which can be applied to investigate numerically particle dispersion problems in similar environments.

In this study, we developed and applied an integrated approach aimed at estimating the risk of infection from SARS-CoV-2 Delta variant of susceptible persons sharing the car cabin with an infected person under the outside air intake conditions (i.e., HVAC system in operation, no recirculation, windows closed). The approach here presented integrates a predictive emission-to-risk approach able to determine the risk of infection from the viral load emitted by the infected subject with the abovementioned validated CFD approach numerically solved using the open-source OpenFOAM software. The integrated approach was applied to different scenarios to evaluate the effect of the following influence parameters: (i) position of the infected subject within the car cabin, (ii) airflow rate of the HVAC system, (iii) HVAC ventilation mode and (iv) inspiratory activity (breathing vs. speaking). A further aim of this study is demonstrating that the risk of infection in indoor environments characterized by fixed seats can be in principle controlled by properly designing the flow patterns of the environment.

2 | MATERIALS AND METHODS

The integrated approach proposed is based on the following steps:

(i) Application of a transient non-isothermal 3D Eulerian-Lagrangian numerical model, developed and validated by the authors in a previous study, to describe particle spread once emitted by an infected speaking/breathing passenger located in a car cabin compartment (section 2.1 and 2.2);

(ii) Description of the emission scenario, that is, definition of the airborne respiratory particle emission rate of an adult while breathing/speaking (section 2.3);
(iii) Calculation of the dose inhaled by the susceptible car occupants for a 30-min journey through the CFD simulations and estimate of the corresponding SARS-CoV-2 infection risk and number of secondary cases on the basis of the predictive emission-to-risk approach previously developed by the authors\textsuperscript{20,45} based on the viral load emitted by the infected subject, the dose of viral load received by the exposed subject, and a dose-response model (section 2.4).

Among possible scenarios that could be considered, we investigated the effect of (i) position of the infected subject within the car cabin, (ii) airflow rate of the HVAC system, (iii) HVAC ventilation mode and (iv) expiratory activity. On the other hand, parameters such as journey duration, car occupancy, and side car windows temperature and opening were considered fixed in the simulations. In particular, as hereinafter detailed, the simulations were performed considering a journey duration of 30 min (as representative of the average duration of business trips by car in Europe\textsuperscript{47}), an occupation of four passengers (i.e., representative of four workers adopting car-sharing/carpooling solutions), and windows completely closed during the whole journey (as likely occurring when driving on trafficked and polluted roads)."

2.1 Eulerian-Lagrangian based model to simulate the airborne particle spread within the car cabin

The mathematical-numerical model was developed using the open-source finite volume-based OpenFOAM software, to have a fully open and flexible tool with complete control of the variables employed for particle dispersion assessment. It is based on an Eulerian-Lagrangian approach, in which the continuum equations are solved for the airflow (continuous phase) and Newton's equation of motion is solved for each particle (discrete phase).

Velocity, pressure, and temperature fields in the car cabin were numerically predicted by solving the mass, momentum, and energy conservation equations under the assumption of three-dimensional, unsteady, turbulent, and compressible flow with ideal gas behavior. Details about governing Partial Differential Equations (PDEs) are widely available in the scientific literature\textsuperscript{48} and are not reported here for brevity.

Turbulence was modeled using the Unsteady Reynolds Averaged Navier Stokes (URANS) approach, and specifically the Shear Stress Transport (SST) $k$-$\omega$ model since the authors in a previous research activity showed that it is the most suitable one to predict airflow patterns within the car cabin under investigation.\textsuperscript{34} Details about the employed URANS turbulence model are available in the scientific literature and are not reported here for brevity.

The computed numerical fields were averaged over a selected time interval to reach a quasi-steady-state condition: once the quasi-steady-state condition is achieved, the flow field is frozen and is used to transport the particles injected by the emitter (i.e., the infected subject) over time during speaking and breathing activities. This approach is exhaustively described in our previous paper\textsuperscript{34} to which the interested reader may refer for further information.

The particle motion inside the airflow was modeled by employing the Lagrangian Particle Tracking (LPT) approach, based on a dispersed dilute two-phase flow. In particular, the spacing between particles is sufficiently large and the volume fraction of the particles sufficiently low ($<10^{-5}$) to justify the use of an Eulerian-Lagrangian approach. The particle motion has been described solving Equations (1) and (2).

\begin{equation}
\frac{m_p}{dt} = F_D + F_g
\end{equation}

\begin{equation}
\frac{dx_p}{dt} = u_p
\end{equation}

where $m_p$ (kg) is the mass of the particle, $u_p$ (m s$^{-1}$) represents the particle velocity, $t$ (s) is the time, $F_D$ (N) and $F_g$ (N) are, respectively, the drag and gravity forces acting on the particle, $x_p$ (m) represents the trajectory of the particle. Details on the calculation of drag and gravity forces are not here reported for the sake of brevity, nonetheless, interested readers may refer to our previous paper\textsuperscript{34} where further information is summarized.

Particle collisions were considered elastic and the equations of motion for the particles are solved assuming a one-way coupling between the continuum phase and the discrete phase: the flow field affects the particle motion whereas the effect of the particles on the airflow is negligible.

2.2 Description of the domain and definition of the boundary conditions and of the scenarios.

The Eulerian-Lagrangian based model, described in Section 2.1, was applied to the analysis of particle dispersion and inhalation in a car cabin evaluating the effects of different geometrical, emission, and thermofluid dynamic influence parameters.

The car cabin sizes are 2.47 $\times$ 1.53 $\times$ 1.19 m, corresponding to a total internal volume of 3.46 m$^3$, which is representative of a "large car" according to the United States Environmental Protection Agency (EPA) Fuel Economy Regulations for 1977 and Later Model Year. Four occupants were considered in the car cabin: the driver sitting in the left front seat and three passengers sitting on the right front seat, right rear seat, and left rear seat, respectively, whereas there was no occupant in the rear middle seat. Three HVAC system ventilation modes were investigated: front ventilation mode (air entering the cabin through four front vents; the sizes of each vent are 10.2 $\times$8.5 cm), windshield defrosting mode (air entering through one vent located under the windshield; the sizes of the vent are 1.33 m $\times$ 1.5 cm) and mixed ventilation (all the five vents
enabled). All the ventilation modes were tested considering outside air intake provided by a HVAC system, which is with no air recirculation; the windows were considered closed for the entire duration of the journey. Different HVAC flow rates (from 10% to 100% of the maximum flow rate), $Q$ ($m^3 \cdot h^{-1}$), were investigated: in particular, the intermediate airflow rate (flow rate at the 50% of the maximum fan capacity, hereinafter referred as $Q_{50\%}$) is set at 216 $m^3 \cdot h^{-1}$ on the basis of the value adopted by Pirouz et al. in their study\textsuperscript{49}; this value is consistent with the intermediate fan capacity reported by Ullrich et al.\textsuperscript{50} for a real car whose internal volume is comparable to that of the cabin model employed for the scenarios under study. We point out that the flow rate also affects the velocity ($u$) at the inlet sections and then the velocity field in the car cabin; moreover, in the simulations here performed a single angle of inlet air-flow rate was adopted. Outlet section positions also have an effect on the velocity field in the car cabin, here the two outlet sections (whose sizes are 17.0 x 8.5 cm) are placed behind the rear seats in the lower-left and lower-right corners as reported in the experimental case study adopted to validate the CFD approach here proposed.\textsuperscript{43,44}

The computational domains employed for numerical simulations are available in Figure 1. The adopted car cabin geometry was built by the authors in a previous study and its description is available in our previous paper,\textsuperscript{34} together with the explanation of the mesh construction strategy.

In the case of front and mixed ventilation mode, the computational domain is the one in the lower right corner of Figure 1: a rectangular duct is connected to each of the front supply openings, allowing the development of the flow velocity profile before entering the cabin through the air vents; when only front ventilation is enabled, the same computational domain is employed but the patch defining the windshield defrosting inlet is modeled as an adiabatic wall (i.e., the vent is closed). On the other hand, for simulation of scenarios where only windshield defrosting vent is enabled, the computational domain is the one in the lower left corner in Figure 1. Boundaries not specified in Figure 1 have been modeled as adiabatic walls.

In Table 1 the boundary conditions imposed for numerical simulations are detailed for the different ventilation modes considered in the present study. Assuming winter climatic conditions, a temperature of 283.15 K was applied to the car windows and inlet air temperature was set to 293.15 K. Passenger face temperatures were set to 306.15 K.\textsuperscript{51} Since a relatively high-velocity fluid flow was numerically simulated and people in the car cabin were supposed to wear winter clothes with a superficial temperature roughly equal to surrounding air, body temperature plume was neglected.

When both front and windshield defrosting inlets are enabled, the airflow rate is split as follows: each front vent introduces the 12.5% of the prescribed flow rate and the windshield vent the 50% remaining. For turbulent quantities the turbulence intensity $I$ (%) and the turbulent mixing length $\ell$ (m) were specified, the latter calculated as the 7% of the characteristic length $L$ (m) assumed equal to the jet width.

The emitter (infected subject) and receiver (susceptible subject) mouths were modeled as circular surfaces with a radius of 2 cm; a temperature equal to 308.15 K was imposed at the mouths of emitter and receiver. As boundary conditions for air velocity at the mouths of emitter and receiver, fixed velocities equal to 1.11 m s$^{-1}$ and 0.32 m s$^{-1}$ in magnitude for speaking and breathing activities were respectively imposed as mean values of sinusoidal during exhalation and inhalation reported by Abkarian et al.\textsuperscript{52} and Cortellessa et al..\textsuperscript{25} In particular, in Cortellessa et al.\textsuperscript{25} we simulated the face-to-face interactions between two subjects in close contact, thus the airflow and particle dynamics were only affected by the breathing/speaking dynamics of emitter and receiver. In the present study, the airflow and particle dynamics are mostly affected by the airflow rates entering (and exiting) the car cabin through the vents,
TABLE 1 Boundary conditions adopted for the different ventilation modes (the computational domain employed for such HVAC system operation mode is pictured in the lower right corner in Figure 1)

| Surface                        | BC for velocity                  | BC for pressure | BC for temperature | BC for k | BC for $\omega$ | Lagrangian |
|--------------------------------|----------------------------------|-----------------|--------------------|----------|------------------|------------|
| Front inlets                   | For mixed-ventilation mode       | $\partial p/\partial n = 0$ | $T = 293.15$ K     | $\ell = 5\%$ | $\epsilon = 0.07$ L rebound |
|                                | For front ventilation mode       | $\partial p/\partial n = 0$ | $T = 293.15$ K     | $\ell = 5\%$ | $\epsilon = 0.07$ L rebound |
|                                | For windshield defrosting        | $\partial p/\partial n = 0$ | $T = 293.15$ K     | $\ell = 5\%$ | $\epsilon = 0.07$ L rebound |
| windshield defrosting inlet    | For mixed-ventilation mode       | $\partial p/\partial n = 0$ | $T = 293.15$ K     | $\ell = 5\%$ | $\epsilon = 0.07$ L rebound |
|                                | For front ventilation mode       | $\partial p/\partial n = 0$ | $T = 293.15$ K     | $\ell = 5\%$ | $\epsilon = 0.07$ L rebound |
|                                | For windshield defrosting        | $\partial p/\partial n = 0$ | $T = 293.15$ K     | $\ell = 5\%$ | $\epsilon = 0.07$ L rebound |
| Outlet sections                | $\partial u/\partial n = 0$     | $p = 101325$ Pa  | $T = 293.15$ K     | $k = 0.1$ m$^2$ s$^{-2}$ | $\partial u/\partial n = 0$ Escape |
| Adiabatic walls                | $u = 0$                          | $\partial p/\partial n = 0$ | $T = 283.15$ K     | $\partial T/\partial n = 0$ standard wall functions |
| Windows                        |                                  |                 |                    |          |                  |            |
| Faces                          |                                  |                 |                    |          |                  |            |
| Emitter mouth                  | Speaking: $|u| = 1.11$ m s$^{-1}$ | $p = 101325$ Pa  | $T = 293.15$ K     | $k = 0.1$ m$^2$ s$^{-2}$ | $\partial u/\partial n = 0$ | Rebound |
|                               | Breathing: $|u| = 0.32$ m s$^{-1}$ |                 |                    |          |                  |            |
| Receiver mouth                 | $|u| = 0.32$ m s$^{-1}$           | $p = 101325$ Pa  | $T = 306.15$ K     | $k = 0.1$ m$^2$ s$^{-2}$ | $\partial u/\partial n = 0$ Escape |
|                                |                                  |                 |                    |          |                  |            |
|                                |                                  | $\partial p/\partial n = 0$ | $T = 306.15$ K     | $k = 0.1$ m$^2$ s$^{-2}$ | $\partial u/\partial n = 0$ | Rebound |

Note: $\partial u/\partial n$ is the partial derivative of velocity with respect to the normal direction, $p$ is the pressure, $T$ is the temperature, $\ell$ is the humidity, $\epsilon$ is the thickness, and $k$ is the thermal conductivity.
moreover, the position, orientation, and distance among the passengers allow not considering the mutual influence of their breathing/speaking dynamics. Thus, adopting constant [mean] expiration and inhalation rates, instead of the sinusoidal dynamics, can be considered an appropriate simplification.

All subjects were assumed mouth-breathers, thus airborne particles were expired and inhaled through the mouth. For particle injection, a random velocity direction from the emitter’s mouth was evaluated as Abkarian et al.\(^\text{52}\) considering a conical jet flow with an angle equal to \(22^\circ\). As concerns the velocity vector direction from the emitter’s mouth, a conical jet flow was considered, adopting a cone angle equal to \(22^\circ\) with random velocity directions in intervals of \(0.1\) s. This adopted angle was calculated by Abkarian et al.\(^\text{52}\) to enclose 90% of the particles in a cone passing through the mouth exit and was verified to remain stable with time after the initial cycles. Finally, as concern the boundary conditions of the particles, the Lagrangian Particle Tracking was solved applying an escape boundary condition over all the surfaces of the computational domain except for entry sections (for which a rebound boundary condition was adopted). In other words, the particles touching the external surfaces (of the domain and of the subjects) disappear and cannot re-enter the computational domain, thus avoiding accumulation of viral load in the environment.

Careful attention was paid to the computational mesh construction: simulations were performed employing hexahedral-based unstructured computational grids, realized employing the open-source snappyHexMesh algorithm. The grid sensitivity analysis was well discussed by Arpino et al.\(^\text{34}\) for the same car cabin computational domain and it is not illustrated here for brevity. The adopted grids are composed of 7899968 cells (mixed and front ventilation scenarios) and 7737311 cells (windshield defrosting ventilation scenario) and were properly refined in correspondence of solid walls and in the jet region, where significant velocity gradients are expected. By way of illustration, the computational grid employed for mixed ventilation and front ventilation scenarios is depicted in Figure 2.

Transient simulations have been performed employing the PIMPLE algorithm, which is a combination of PISO (Pressure Implicit with Splitting of Operator) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations), simulating the overall transient phenomenon as consecutive steady-state time steps; specifically, when the number of iterations (for a specific time-step) reaches the convergence, the algorithm will move on to the next time step until the solution of the investigated phenomenon is complete. In our simulations, a time step of \(0.1\) s was adopted and as criterion for time step convergence we considered the absolute tolerance of the solver \(<10^{-5}\).

The risk of infection was evaluated for different exposure scenarios aimed at evaluating the effect of influence parameters under investigation. In particular, the following influence parameters were analyzed: (i) influence of the position of the infected subject in the car cabin (i.e., driver vs. passenger sitting on the right rear seat), (ii) influence of the HVAC system flow rate (i.e., from 10% to 100% of the maximum flow rate, hereinafter also referred as airflow ratio), (iii) influence of the HVAC ventilation mode (i.e., mixed, front, and windshield defrosting), (iv) influence of the expiratory activity (i.e., breathing vs speaking). The scenarios and the corresponding parameters adopted in the simulations are summarized in Table 2. Please note that the exposed susceptible subjects were considered breathing through the mouth while sitting.

\subsection{2.3 Particle emission}

Particle emission from the infected subject was modeled as a function of the expiratory activity, that is, speaking\(^{25}\) and breathing.\(^{46}\) In particular, the particle number emission rate (\(ER_{np}\) particle s\(^{-1}\)), that is, the size-dependent number of particles exhaled by the infected subject per unit time, was estimated for speaking and breathing on the basis of the experimental analyses carried out by Johnson et al.\(^{53,54}\) Indeed, they measured the number distribution of the particles in the range 0.5–1000 \(\mu\)m in the close proximity of the mouth of an adult person while breathing and speaking. This measurement is extremely complex due to the quick evaporation phenomenon typical of the respiratory particles as soon as they are emitted. For further details on the experimental apparatus and the methodology adopted, the readers are kindly suggested
TABLE 2  Scenarios investigated through CFD analyses: definition of the parameters adopted to evaluate the effect of the influence parameters

| Scenarios investigated | 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 of Figure 1) | $Q_{10\%}$ | 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 | $Q_{10\%}$ | Mixed, front, windshield defrosting | Speaking |
| Influence of the expiratory activity | Driver | $Q_{10\%}$ | Windshield defrosting | Speaking, breathing |

TABLE 3  Particle number ($dN/d\log(d_{p})$) and volume ($dV/d\log(d_{p})$) distributions pre- and post-evaporation fitted by five size ranges as adopted in the simulations for breathing and speaking expiratory activities. Particle number ($ER_{n}$) and volume ($ER_{v}$) emission rates are also reported.

| Expiratory activity | Pre-evaporation | Post-evaporation |
|---------------------|-----------------|------------------|
|                     | Particle diameter (size range), $d_{p}$ ($\mu m$) | $dN/d\log(d_{p})$ (part. cm$^{-3}$) | $dV/d\log(d_{p})$ (µl cm$^{-3}$) | $ER_{n}$ (part. s$^{-1}$) | $ER_{v}$ (µl s$^{-1}$) | Particle diameter (size range), $d_{p}$ ($\mu m$) | $dV/d\log(d_{p})$ (µl cm$^{-3}$) |
| breathing           | 2.4 $\mu m$ ($<1.9-3.2 \mu m$) | 0.312 | $2.33 \times 10^{-9}$ | 32.6 | $2.43 \times 10^{-7}$ | 0.5 $\mu m$ ($<0.7 \mu m$) | 2.33 $\times 10^{-11}$ |
|                     | 4.1 $\mu m$ (3.2-5.4 $\mu m$) | 0.016 | $5.80 \times 10^{-10}$ | 1.6 | $6.11 \times 10^{-8}$ | 0.9 $\mu m$ (0.7-1.2 $\mu m$) | 5.80 $\times 10^{-12}$ |
|                     | 7.1 $\mu m$ (5.4-9.3 $\mu m$) | 0.005 | $1.03 \times 10^{-9}$ | 0.6 | $1.09 \times 10^{-7}$ | 1.5 $\mu m$ (1.2-2.0 $\mu m$) | 1.03 $\times 10^{-11}$ |
|                     | 16.0 $\mu m$ (9.3-27.3 $\mu m$) | 0.001 | $2.15 \times 10^{-9}$ | 0.2 | $4.52 \times 10^{-7}$ | 3.4 $\mu m$ (2.0-5.9 $\mu m$) | 2.15 $\times 10^{-11}$ |
|                     | 35.8 $\mu m$ (27.3-46.9 $\mu m$) | <0.001 | $3.44 \times 10^{-13}$ | <0.1 | $3.63 \times 10^{-11}$ | 7.7 $\mu m$ (5.9-10.1 $\mu m$) | 3.44 $\times 10^{-15}$ |
|                     | Total            | 0.078 | $1.92 \times 10^{-9}$ | 33.4 | $8.65 \times 10^{-7}$ | Total | 1.92 $\times 10^{-11}$ |
| speaking            | 4.6 $\mu m$ ($<0.5-4.6 \mu m$) | 0.266 | $1.39 \times 10^{-8}$ | 217.6 | $1.14 \times 10^{-5}$ | 1 $\mu m$ ($<1 \mu m$) | 1.39 $\times 10^{-10}$ |
|                     | 9.0 $\mu m$ (4.6-17.7 $\mu m$) | 0.035 | $1.33 \times 10^{-8}$ | 20.3 | $7.81 \times 10^{-6}$ | 1.9 $\mu m$ (1.0-3.8 $\mu m$) | 1.33 $\times 10^{-10}$ |
|                     | 23.2 $\mu m$ (17.7-30.4 $\mu m$) | 0.013 | $8.75 \times 10^{-8}$ | 3.1 | $2.05 \times 10^{-5}$ | 5 $\mu m$ (3.8-6.6 $\mu m$) | 8.75 $\times 10^{-10}$ |
|                     | 45.5 $\mu m$ (30.4-68.2 $\mu m$) | 0.016 | $8.08 \times 10^{-7}$ | 5.7 | $2.83 \times 10^{-4}$ | 9.8 $\mu m$ (6.6-14.7 $\mu m$) | 8.08 $\times 10^{-9}$ |
|                     | 78 $\mu m$ (68-90 $\mu m$) | 0.015 | $3.83 \times 10^{-6}$ | 1.8 | $4.48 \times 10^{-4}$ | 16.8 $\mu m$ (14.7-19.2 $\mu m$) | 3.83 $\times 10^{-8}$ |
|                     | Total            | 0.249 | $7.71 \times 10^{-7}$ | 248.6 | $7.71 \times 10^{-4}$ | Total | 7.71 $\times 10^{-9}$ |

referring to the above-mentioned papers.$^{53,54}$ Here, for the sake of brevity, we just show the simplified particle number distributions considered to make the simulations affordable: indeed, we have fitted the original distributions$^{53,54}$ through simplified distributions made up of five size ranges. Due to the negligible contribution to the infection risk of spray borne respiratory particles demonstrated in previous papers,$^{25,55,56}$ the five size ranges here considered are limited to the airborne respiratory particle range (<90 $\mu m$). Volume distributions and emission rates ($ER_{v}$, µl s$^{-1}$) were calculated considering the particles as sphere. Since the evaporation phenomenon occurs quickly as soon as the particles are emitted,$^{57,58}$ the post-evaporation volume distribution was considered in the CFD model. Indeed, the volume particle distribution before evaporation (i.e., as emitted) was reduced to that resulting from the quick evaporation considering a volume fraction of non-volatiles in the initial particle of 1%.$^{57}$ This particle evaporation phenomenon reduces the particle diameter to about 20% of the emitted size. On the contrary, the number of particles remains unchanged during the evaporation process. The particle
number and volume distributions pre- and post-evaporation (fitted by five size ranges) adopted in the simulations and the corresponding number and volume emission rates are summarized in Table 3 for both the expiratory activities investigated.

2.4 | Estimation of the dose received by the susceptible subjects and infectious risk assessment

The risk of infection of the exposed subjects can be calculated based on the dose of viral load (RNA copies considering the viable/infec-
tious fraction) received by susceptible subjects as they inhale virus-
laden respiratory particles emitted by the infected subject. Then, a
dose-response model is adopted to convert the dose of viral load into a risk of infection.

The dose of viral load is the product of the respiratory particle
dose received by the susceptible subjects during the exposure event
and the viral load carried by the airborne respiratory droplets emit-
ted by the infected subject. The viral load \( (c_v) \) carried by the particles
was retrieved from data currently available from the scientific liter-
ature. Here we adopted the viral load of the Delta variant (B.1.617.2
SARS-CoV-2) which is dominant across much of the world at the time
of writing. In particular, we fit the \( c_v \) distribution data provided by
Teyssou et al.\(^{59}\) (median value of 7.83 log\(_{10}\) RNA copies ml\(^{-1}\)) with
a quartile simulation approach, and in other words, we performed a
Monte Carlo simulation using proportionally selecting random val-
ues within each quartile (1\(^{st}\) quartile range 4.3–6.3 log\(_{10}\) RNA copies
ml\(^{-1}\), 2\(^{nd}\) quartile range 6.3–7.8 log\(_{10}\) RNA copies ml\(^{-1}\), 3\(^{rd}\) quartile
range 7.8–8.8 log\(_{10}\) RNA copies ml\(^{-1}\), 4\(^{th}\) quartile range 8.8–9.4 log\(_{10}\)
RNA copies ml\(^{-1}\)) to obtain 20,000 \( c_v \) values. The respiratory particle
dose received by each susceptible subject in the car cabin is evalu-
ated through both CFD analyses and well-mixed approach.

2.4.1 | CFD analyses

The dose of RNA copies carried by respiratory airborne particles and
then inhaled by the susceptible subject for each \( c_v \) value \( (D(c_v)) \) was

\[
D(c_v) = c_v \int_0^T V_{p,pre}(t) \, dt \quad \text{(RNA copies)} \quad (3)
\]

where \( V_{p,pre}(t) \) is the doses of airborne particles inhaled as a function
of the exposure time \( t \), and \( T \) is the total exposure time (30 min). We
highlight that the viral load carried by the respiratory particle is related
to the initial particle volume (i.e., before evaporation) since the evap-
oration leads to a reduction in the particle volume (the RNA copies do
not evaporate); thus, the \( V_{p,pre} \) term has been adopted as the dose of
airborne particles calculated with the initial (pre-evaporation) volume.
On the contrary, the actual dose in terms of volume of respiratory par-
ticles inhaled by the susceptible occupants is referred to as the actual
volume at the time of inhalation (i.e., post-evaporation; hereinafter
referred as \( V_{p,post} \)). Indeed, we highlight that the respiratory particles
dynamics is driven by the post-evaporation particle size, whereas the
viral load they carry is a function of the pre-evaporation particle size.

From the dose viral load (i.e., the dose of RNA copies), the
probability of infection of the exposed subject for each \( c_v \) \((P(c_v))\)
was calculated adopting a well-known exponential dose-response
model\(^{29,60}\):

\[
P_I(c_v) = 1 - e^{-\frac{c_v}{HID_{63}}} \quad (\%) \quad (4)
\]

where \( HID_{63} \) represents the human infectious dose for 63% of sus-
ceptible subjects, that is, the number of RNA copies needed to initiate
the infection with a probability of 63%. For SARS-CoV-2, a \( HID_{63} \) value
of \( 7 \times 10^2 \) RNA copies was applied as recently estimated by Gale.\(^{61}\)
We note that in subsequent work Gale\(^{62}\) increased the RNA copy-
to-plaque-forming unit (pfu) ratio used in the thermodynamic dose-
response model from 3.6 \times 10^2 (based on Vicenzi et al.\(^{63}\)) to 10^2 RNA
copies:pfu, which improves agreement with the dose-response esti-
mates of Zhang and Wang.\(^{64}\) This adjustment increases the \( HID_{63} \) value
approximately thirtyfold to \( 2 \times 10^4 \) RNA copies.\(^{62}\) However, using the
golden Syrian hamster model, Hawks et al.\(^{65}\) found RNA levels in air
samples to be ~200 times higher than pfu levels one and two days
postinoculation, with infectious virus non-detect afterward despite
the persistence of RNA detections. This indicates a kinetic aspect to
the RNA:pfu ratio likely associated with the immune response that
affects the infectious virus fraction.\(^{64}\) As we are focused on model-
ing the early time period of infection for an infected host previously
naive to SARS-CoV-2, we maintain use of the \( HID_{63} \) value of \( 7 \times 10^2 \)
RNA copies herein, which is also generally consistent with the pre-
dictions of a novel dose-response approach developed by Henrques
et al.\(^{66}\) Furthermore, variants of concern such as Delta and Omicron
may have greater infectiousness with a lower \( HID_{63} \), providing another
reason to continue with the original model of Gale\(^{61}\) given the great
uncertainty in the dose-response model for humans.

In order to consider the range of possible viral load values, the
individual risk of infection (\( R \)) of each exposed passenger was calcu-
lated through a Monte Carlo simulation with 20,000 realizations, in
which the viral load \( (c_v) \) was sampled randomly from the previously
defined distribution and then assigned as the RNA concentration of
the exhaled particle volume to calculate the inhaled dose of RNA
copies (\( D \)) and resulting probability of infection (\( P_I \)) for each realiza-
tion. The mean of the 20,000 \( P_I \) values is calculated as the individual
risk (\( R \)) for each passenger based on their respective inhaled doses.

2.4.2 | Well-mixed approach

To compare the risks of infection obtained through the detailed
CFD analyses proposed here with to this we would have calculated
adopting the well-mixed hypothesis, the risk of infection of the sus-
ceptible subjects was also assessed adopting the simplified zero-
dimensional model assuming complete and instantaneous mixing
TABLE 4  Doses in terms of volume of airborne respiratory particle (V_p,mt) inhaled by susceptible occupants of the car cabin and their individual infection risk for different position of the infected subject (driver vs. passenger #3) in case of mixed ventilation at \( Q_{50\%} \), speaking activity, and 30-min exposure scenario. Infection risks evaluated through the well-mixed approach are also reported.

| Driver infected | Individual infection risk | Passenger #3 infected | Individual infection risk |
|-----------------|---------------------------|------------------------|---------------------------|
| Susceptible subject | Inhaled volume (ml) | (%) | CFD | Well-mixed | Susceptible subject | Inhaled volume (ml) | (%) | CFD | Well-mixed |
| Driver          | Emitter                  | 1.89 x 10^{-9} | 9.2%  | 42%          | 5.17 x 10^{-11} | 0.30%  | 42%          |
| Passenger #1    | 4.49 x 10^{-9}          | 18% |       |               | 1.42 x 10^{-9} | 7.2% |               |
| Passenger #2    | 8.68 x 10^{-9}          | 26% |       |               | 1.59 x 10^{-11} | 0.09% |               |
| Passenger #3    | 4.49 x 10^{-9}          | 18% |       |               | Emitter          |       |               |

of the viral emission. In this case, the dose of RNA copies received by the susceptibles was estimated on the basis of the average well-mixed viral load concentration in the car cabin \( C_{v,avg} \) (RNA copies m\(^{-3}\)) over the course of the 30-min journey, based on the analytical solution of Miller et al. \( [26] \):

\[
C_{v,avg} (c_v, t) = \frac{E_v (c_v)}{V_{cabin} \times IVRR} \left( 1 - \frac{1}{IVRR \times t} (1 - e^{-IVRR t}) \right) \quad \text{(RNA copies m}^{-3}\text{)}
\]  

(5)

where \( V_{cabin} \) (m\(^3\)) is the volume of the car cabin under investigation, \( IVRR \) (h\(^{-1}\)) represents the infectious virus removal rate in the space investigated, and \( E_v \) is the viral load emission rate (RNA copies h\(^{-1}\)). \( IVRR \) is the sum of three contributions\(^{67}\): the particle deposition on surfaces \( (k, \) here assumed equal to 0.24 h\(^{-1}\) \( \times \mu m\)) the viral inactivation \( (j, \) here assumed equal to 0.63 h\(^{-1}\)) and the average air exchange rate via ventilation (AER, h\(^{-1}\)). The latter was calculated as the ratio between the airflow rate provided by the HVAC systems and the cabin volume: AERs were equal to 12.5, 31.2, 62.4, 93.6, and 124.9 h\(^{-1}\) at \( Q_{10\%}, Q_{25\%}, Q_{50\%}, Q_{75\%}, \) and \( Q_{100\%} \) flow rates, respectively. \( E_v \) was calculated as the product of the viral load \( (c_v) \) obtained from simulation as described previously and the cumulative, pre-evaporation airborne volume emission rate \( (E_v) \) obtained from Table 5 (i.e., 7.71 x 10^{-4} and 8.65 x 10^{-7} ml s\(^{-1}\) for speaking and breathing, respectively.

The dose of RNA copies inhaled by the exposed subject was then estimated as:

\[
D (c_v, t) = IR \cdot C_{v,avg} (c_v, t) \cdot t \quad \text{(RNA copies)}
\]  

(6)

with \( IR \) being the inhalation rate and equal to 0.54 m\(^3\) h\(^{-1}\) for an adult just breathing while sitting.\(^{69,70}\)

As with the analysis based on the CFD results, a Monte Carlo simulation was performed to estimate the individual risk \( (R) \) of each susceptible passenger based on the viral load of the emitting host. For speaking, a simulation to calculate \( R \) using Equation (4) was performed for each of the three ER\(_v\) values presented earlier. The distribution of secondary cases and \( R_{even} \) were calculated using the Bernoulli trial approach (Equation (7)) for the most representative well-mixed scenarios as further described in Section 3.

In terms of the emission rate in units of infectious doses of Delta SARS-CoV-2, or "quanta" when considering the HID\(_{avg}\), the equivalent values modeled herein for the 25th, 50th, and 75th percentile viral loads for speaking are 8.0, 252, and 2524 quanta h\(^{-1}\) for the pre-evaporation volume up to 90 \( \mu m \) in diameter. There are no literature values for comparison for the Delta or Omicron variants, but a recent Omicron outbreak at a party in a restaurant in Norway\(^7\) suggests high emission rates are likely. For example, using Equations (4–6) for a ca. 145 m\(^2\) room with 3 m ceilings and a 74% probability of infection for a 4.5-hour exposure leads to emission rate estimates of 470 and 1650 quanta h\(^{-1}\) for IVRR values of 1.5 and 6.0 h\(^{-1}\), respectively, using an IR of \(-0.5 \) m\(^3\) h\(^{-1}\). Thus, the emission rates evaluated herein appear plausible also considering the rapid spread of both Delta and Omicron variants.

2.4.3  |  Probability of secondary transmission

Beyond the individual risk, which is the mean of an overdispersed distribution and thus masks substantial variability in outcomes, it is of interest to calculate the probability of secondary transmission from the car journey, which is a function of the number of susceptible occupants of the car \( (S) \). Specifically, the probability of discrete numbers of secondary cases \( (C) \) arising can be estimated using a Bernoulli trial approach, which is an improvement over past works\(^{21,22}\) using the percentile values of a continuous distribution of \( C \) obtained from the simple product of \( R \) and \( S \) for each realization. Similar to the methodology of Goyal et al.\(^22\) we model successful transmission for each passenger (assuming all passengers are fully susceptible) by drawing a random uniform variable \( U(0,1) \) and comparing it with the \( P_i \) value for that passenger, with successful transmission occurring when \( U(0,1) < P_i \). This was performed for each of the three susceptible passengers for each realization, and the number of secondary cases \( (C) \) for an individual realization was calculated by summing up the successful trials as follows:

\[
C = \sum_{i=1}^{S-3} Ber(P_i)_3 \quad \text{(secondary cases)}
\]  

(7)
The end result of the simulation is a discrete probability distribution of secondary cases (C), with the mean value representing the event reproduction number ($R_{event}$) of the 30-min car journey in accordance with the definition of Tupper et al.\textsuperscript{73}

3 | RESULTS AND DISCUSSION

3.1 | Influence of the position of the infected subject in the car cabin

Table 4 presents the results of doses in terms of volume of airborne respiratory particle inhaled ($V_{p\text{-}post}$) by susceptible occupants of the car cabin and their individual infection risk for different positions of the infected subject (driver vs. passenger #3) in case of mixed ventilation at 50% of the maximum HVAC flow rate ($Q_{50\%}$), speaking activity and 30-min exposure scenario. Individual risks evaluated through the analytical, zero-dimension well-mixed approach is also reported.

Results show that, in the case of driver infected, the highest dose ($8.68 \times 10^{-9}$ ml) and individual risk (26%) are received by the passenger #2 (left rear seat, i.e., just behind the driver), whereas the passenger #1 (front right seat, i.e., just on the right side of the driver) receives the lowest dose ($1.89 \times 10^{-9}$ ml) and risk (9.2%). Lower doses and risks are received by when the infected passenger #3: the highest dose ($1.42 \times 10^{-9}$ ml) and individual risk (7.2%) are received by the passenger #1, whereas risks lower than 1% are received by the driver and the passenger #2.

The reason for such different exposure and risk conditions of the susceptible occupants, occurring as a function of the position of the infected subject, is strictly related to the specific airflow pattern in the car cabin. This is graphically reported in Figure 3, Figure 4, and Figure 5 where streamlines (both from the HVAC vents and infected driver while speaking) and mean velocity contours as well as the spatial distributions of the airborne respiratory particles after 30 min are reported for the driver infected scenario. Figure 3 clearly shows that the streamlines of the airflows entering the domain from the HVAC system move from the vents, likely carrying the respiratory particles emitted by the driver (slightly moving upwards due to the warm buoyant air exhaled) and conveying them toward the passenger just sitting behind him (passenger #2). In fact, the Figure 4 demonstrates that the airflow emitted by the driver is conveyed to the back seats by the airflow coming from the front and windshield vents; as a consequence, higher exposure to respiratory particles of the passenger #2 occurs as also shown by the spatial distributions of the airborne respiratory particles (Figure 5).

A completely different airborne particle distribution can be observed in Figure 6 when the passenger #3 is the infected. This is clearly shown in Figure 7 where the airflows exiting the mouth of the infected passenger #3 are graphed. In fact, the airflow emitted by the passenger #3 almost reaches the passenger #1 and then is immediately redirected toward the outlet sections by the HVAC system airflow. In such condition, the airborne particles are mainly confined in the rear seats. Anyway, due to the large inertia typical of super-micrometric particles, the respiratory particles emitted by the passenger #3 are likely not able to follow the airflow then leading to a larger exposure (and consequently dose and risk) of the passenger #1, that is, the passenger sitting just ahead of the infected subject, with respect to other occupants as represented in Figure 6.

For the well-mixed analytical solution, the individual risk is 42% for all passengers regardless of position. This value overestimates the risks received by susceptible subjects in the case of driver infected estimated through the CFD (maximum values 26%) and, even more, the one they receive for the case of passenger #3 being infected (maximum risk 7.2%). The overestimation resulting from the well-mixed approach demonstrates the effectiveness of the HVAC system in reducing the exposure of passengers to virus-laden particles through flow patterns allowing a cleaner air in their breathing zones.

3.2 | Influence of the HVAC system flow rate

In Table 5 results of doses in terms of volume of airborne respiratory particle ($V_{p\text{-}post}$) inhaled by susceptible occupants of the car cabin and their individual infection risk for different HVAC flow rates...
(expressed as airflow ratio with respect to the maximum flow rate) in case of mixed ventilation, driver infected, speaking activity, and 30-min exposure scenario is reported.

When the driver is the infected subject, as already shown in the previous section, the highest doses and risks are (in most of the cases) received by the passenger just sitting behind him/her (passenger #2). As expected, the dose and risk values are strongly influenced by the flow rate provided. As an example, for passenger #2, the risk is <1% for very high flow rates (i.e., ≥Q75%) but it strongly increases with airflow ratios ≤Q50% reaching an individual risk of ~50% for Q10%. Similar trends were found for the other passengers with maximum infection risks equal to 32% and 51%, at Q10%, for passengers #1 and #3, respectively. Nonetheless, despite a general decreasing trend of the risk as the HVAC flow rate increases, we point out that the risk of the passengers sitting on the back does not constantly reduce, for example, the risks at Q25% and Q75% are lower than at Q50% and Q100%, respectively. This is due to the specific airflow patterns occurring at those flow rates which likely undermine the effectiveness of the particle removal toward the exit sections.

In case of low air exchange rate (Q10%) the lowest difference among the passengers in terms of risk of infection was detected. This is likely related to the lowest efficiency of the HVAC system in conveying the virus-laden respiratory particles toward the outlet sections, then letting them disperse within the car cabin: indeed, the ratio between the maximum and minimum risk values decreases with the HVAC flow rate then demonstrating a more homogenous concentration. In this respect, it is not surprising that the closest match of the well-mixed results to the average passenger risk calculated through the CFD approach occurs with Q10% (~12.5 air changes per hour). In this case, the CFD-based passenger risks for passengers
**FIGURE 6** Spatial particle distribution after 30 min in case of mixed ventilation mode at 50%, speaking activity, passenger #3 infected.

**FIGURE 7** Streamlines of the airflows (colored by velocity) exiting the mouth of the infected passenger #3 in case of mixed ventilation mode at 50% (Q50%) and speaking activity.

**TABLE 5** Doses in terms of volume of airborne respiratory particle ($V_{p,post}$) inhaled by susceptible occupants of the car cabin and their individual infection risk for different HVAC flow rates ($Q_{10\%}$ to $Q_{100\%}$) in case of mixed ventilation, driver infected, speaking activity, and 30-min exposure scenario. Infection risks evaluated through the well-mixed approach are also reported.

| HVAC airflow ratio | Inhaled volume (ml) | Individual infection risk (%) |
|--------------------|---------------------|-------------------------------|
|                    | Passenger #1 | Passenger #2 | Passenger #3 | Passenger #1 | Passenger #2 | Passenger #3 | All Passengers |
| $Q_{100\%}$       | 0           | $1.32 \times 10^{-10}$ | $5.22 \times 10^{-10}$ | 0            | 0.76%       | 2.9%         | 35%            |
| $Q_{75\%}$        | $4.59 \times 10^{-12}$ | $7.97 \times 10^{-11}$ | $3.62 \times 10^{-10}$ | 0.03%        | 0.46%       | 2.0%         | 38%            |
| $Q_{50\%}$        | $1.89 \times 10^{-9}$ | $8.68 \times 10^{-9}$ | $4.49 \times 10^{-9}$ | 9.2%         | 26%         | 18%          | 42%            |
| $Q_{25\%}$        | $1.87 \times 10^{-8}$ | $1.67 \times 10^{-9}$ | $1.42 \times 10^{-9}$ | 36%          | 8.3%        | 7.2%         | 48%            |
| $Q_{10\%}$        | $8.30 \times 10^{-8}$ | $1.02 \times 10^{-7}$ | $1.37 \times 10^{-8}$ | 51%          | 53%         | 32%          | 55%            |
#1 and #2 are >50% and in good agreement with the well-mixed approach (55%). Conversely, when the airflow ratio is \( Q_{50\%} \), as shown in the previous section, the risk is significantly overestimated using the well-mixed approach.

We point out that all the scenarios here presented consider the HVAC system in operation under the outside air intake conditions; when the HVAC system is not in operation, or it is operated under recirculation ventilation conditions, the actual air exchange rate is clearly lower. Indeed, it is mainly due to the leakages of the car cabin and of the ducts, for this reason, it is strongly affected by the velocity of the vehicles: previous papers showed that the air exchange rate can be lower than 5 h\(^{-1}\) \( , \) \( , \) \( , \) \( , \) \( , \) that is, well below that obtained under the outside air intake condition at \( Q_{10\%} \) flow rate here investigated. For such lower AER values, based on what we have shown above, the well-mixed approach can be considered a useful tool to roughly estimate the risk of exposed subjects: as an example, for a ventilation condition with air recirculation characterized by an AER equal to 2 h\(^{-1}\), the estimate of the risk of infection for the passengers provided by the well-mixed approach is >60%.

### 3.3 Influence of the HVAC ventilation mode

In Table 6 the doses in terms of volume of airborne respiratory particle \( V_{p, \text{post}} \) inhaled by susceptible occupants of the car cabin and their individual infection risk for different HVAC ventilation mode in case of \( Q_{50\%} \) flow rate, driver infected, speaking activity, and 30-min exposure scenario is reported.

Data clearly highlight that the ventilation mode strongly affects the risk of the passengers. For mixed ventilation mode (air entering the cabin through four front vents), as shown in previous sections, the highest dose is received by the passenger #2 (individual risk 26% at \( Q_{50\%} \)). Nonetheless, the worst exposure condition is experienced by the passengers for windshield defrosting mode (air entering through one vent located under the windshield) since the risks their passengers range from 22% (passengers #3) to 59% (passenger #2). When a front ventilation mode is adopted the risks of the passengers range from 22% (passengers #3) to 59% (passenger #2). In case of front ventilation mode, the airflow entering in the cabin impacts the front seats and passengers, changes its direction and forms a recirculation area (Figure 8), then higher concentrations of respiratory particles occur in the front compartment, preventing their spread toward the rear seats (Figure 9) during the whole journey.

On the contrary, in the case of windshield defrosting mode, the respiratory particles emitted by the driver and moving upwards due to the buoyancy forces, are transported in the rear region of the car cabin by the airflow injected through the windshield vent not encountering any obstacle as graphically represented by both the streamlines of the airflows from the inlet vents (Figure 10) and those exiting the mouth of the infected driver (Figure 11). As a direct consequence of both the airflow patterns and the infected subject position, the airborne particles are mainly confined in the left region of the car (Figure 12) then explaining the reason why the passenger #2 is the most exposed.

Having shown these differences in terms of risk of infection among the ventilation modes, the well-mixed solution provides a reasonable approximation of the results for the windshield defrosting mode, whereas the front ventilation mode is clearly the least well mixed within the car cabin, and therefore the zero-dimension model significantly overestimates the risk for the back seat passengers by over two orders of magnitude.

### 3.4 Influence of the expiratory activity: breathing vs. speaking

In Table 7 the doses in terms of volume of airborne respiratory particle \( V_{p, \text{post}} \) inhaled by susceptible occupants of the car cabin and their individual infection risk are compared for the two expiratory activities (breathing and speaking) in case of \( Q_{50\%} \) flow rate, windshield defrosting ventilation mode, driver infected, and 30-min exposure scenario. Infection risks evaluated through the well-mixed approach are also reported.

### TABLE 6

| HVAC ventilation mode       | Inhaled volume (ml) | Individual infection risk (%) |
|----------------------------|---------------------|-------------------------------|
|                            | Passenger #1        | Passenger #2                  | Passenger #3                  | All Passengers |
|                            | CFD                 | CFD                           | CFD                           | All Passengers |
| Front mode                 | \( 1.13 \times 10^{-7} \) | \( 2.99 \times 10^{-11} \)  | \( 9.74 \times 10^{-12} \)  | 53%           | 0.17% | 0.06% | 42% |
| Windshield defrosting mode | \( 1.36 \times 10^{-8} \) | \( 2.29 \times 10^{-7} \)  | \( 6.31 \times 10^{-9} \)  | 32%           | 59%   | 22%   |     |
| Mixed mode                 | \( 1.89 \times 10^{-9} \) | \( 8.68 \times 10^{-9} \)  | \( 4.49 \times 10^{-9} \)  | 9.2%           | 26%   | 18%   |     |

These data can be better explained by referring to the streamlines, main velocity contours, and spatial particle distributions. Flow patterns for mixed ventilation mode have been already discussed in the section 3.1, where, for driver infected scenario, the accumulation of respiratory particles in the breathing zone of the passenger #2 has been demonstrated. In case of front ventilation mode, the airflow entering in the cabin impacts the front seats and passengers, changes its direction and forms a recirculation area (Figure 8), then higher concentrations of respiratory particles occur in the front compartment, preventing their spread toward the rear seats (Figure 9) during the whole journey.

On the contrary, in the case of windshield defrosting mode, the respiratory particles emitted by the driver and moving upwards due to the buoyancy forces, are transported in the rear region of the car cabin by the airflow injected through the windshield vent not encountering any obstacle as graphically represented by both the streamlines of the airflows from the inlet vents (Figure 10) and those exiting the mouth of the infected driver (Figure 11). As a direct consequence of both the airflow patterns and the infected subject position, the airborne particles are mainly confined in the left region of the car (Figure 12) then explaining the reason why the passenger #2 is the most exposed.

Having shown these differences in terms of risk of infection among the ventilation modes, the well-mixed solution provides a reasonable approximation of the results for the windshield defrosting mode, whereas the front ventilation mode is clearly the least well mixed within the car cabin, and therefore the zero-dimension model significantly overestimates the risk for the back seat passengers by over two orders of magnitude.
exposure scenario (which represents the worst exposure condition among those reported in previous section). In the case of breathing, very low airborne particle volumes are inhaled by all the passengers leading to negligible risks of infection (well below 1%): this is due to the low amount of particles emitted and their reduced velocity at the exit of the infected subject’s mouth (please see the emission rate discussed in Section 2.3). In the case of breathing activity of the infected subject, the most exposed susceptible is the passenger #3 (not passenger #2 as resulting from speaking activity) and his/her risk (although negligible) is ten-fold the one received by the other two passengers. The difference between speaking and breathing activities can also be visually observed comparing the spatial particle distributions of Figure 12 (speaking activity) and Figure 13 (breathing activity) where the latter clearly shows a much lower particle concentration in the car cabin. For the case of breathing, as already reported for speaking, the well-mixed analytical solution provides a rough estimate of the average passenger risk (~0.2% versus ~0.07%).

3.5 Distribution of secondary cases

Results of the Bernoulli trial calculations reporting the probability of discrete numbers of secondary cases and the $R_{even}$ are summarized in Figure 14 for different scenarios. All the scenarios tested through the CFD approach are reported as well as the two scenarios presenting well-mixed results comparable to the CFD ones, that is, mixed-mode ventilation at $Q_{10\%}$ flow rate for speaking and mixed-mode ventilation at $Q_{50\%}$ flow rate for breathing.
FIGURE 10 Streamlines of the airflows entering the domain from the inlet vents and mean velocity contours on x-y slices at z = −0.38 m and z = 0.38 m in case of windshield defrosting ventilation mode at 50% (Q50%), speaking activity, and driver infected.

FIGURE 11 Streamlines of the airflows (colored by velocity) exiting the mouth of the infected driver in case of windshield defrosting ventilation mode at 50% (Q50%), speaking activity, and driver infected.

FIGURE 12 Spatial particle distribution after 30 min in case of windshield defrosting ventilation mode at 50% (Q50%), speaking activity, and driver infected.
The Bernoulli trial data show that there are three model scenarios where the average number of secondary cases ($R_{\text{event}}$) exceeds 1 (the $Q_{10\%}$ flow rate condition for both well-mixed and CFD models, and the windshield defrosting mode at the $Q_{50\%}$ flow rate). Supporting the use of the well-mixed approach for $Q_{10\%}$ flow rate, the distribution of secondary cases ($C$) is also very similar to that obtained from CFD, with the probability of zero cases being ~40% and thus the probability of at least one transmission occurring being ~60%. There are three speaking scenarios for which there is over a 90% probability of nobody being infected ($C = 0$) (mixed mode with driver infected at $Q_{25\%}$ and $Q_{100\%}$, and mixed mode with passenger infected at $Q_{50\%}$). For the front mode scenario, there is high risk for the front seat passenger, but the probability that none of the back seat passengers gets infected is over 99%. Thus, the front mode is a viable ventilation strategy when the driver is infected and no passenger sits in the front seat, as there is effective aerodynamic containment between the front and back of the car. For the breathing emission rates evaluated herein, there is very low probability of a secondary transmission (~0.2%) for the 30-min journey.

### 3.6 Strengths and weaknesses

The results showed in the previous sections highlight the strengths of the CFD approach for a proper evaluation of the risk of infection in small, confined spaces affected by a particular fluid dynamic due to high flow rates entering the cabin, or ventilation systems not designed for mixing (e.g., front). Simplified analytical approaches, such as zero-dimensional models, may inaccurately estimate the risk of the exposed subject by a large amount. However, for the 10% flow condition and mixed-mode ventilation, the zero-dimension well-mixed approach produces quite similar results in terms of both the average risk (and thus $R_{\text{event}}$) and the probability distribution of secondary cases. The parameters under which well-mixed approaches are most defensible requires further evaluation, using CFD and possibly

### TABLE 7

| Expired Activity | Inhaled volume (ml) | Individual infection risk (%) |
|------------------|---------------------|-------------------------------|
|                  | Passenger #1 | Passenger #2 | Passenger #3 | Passenger #1 | Passenger #2 | Passenger #3 | All Passengers |
| Breathing        | $2.53 \times 10^{-12}$ | $2.18 \times 10^{-12}$ | $3.06 \times 10^{-11}$ | 0.01% | 0.01% | 0.18% | 0.21% |
| Speaking         | $1.36 \times 10^{-8}$ | $2.29 \times 10^{-7}$ | $6.31 \times 10^{-9}$ | 32% | 59% | 22% | 42% |

*FIGURE 13* Spatial particle distribution after 30 min in case of windshield defrosting ventilation mode at 50% ($Q_{50\%}$), breathing activity, and driver infected.
As an example, we have not considered: (i) the effect of mitigation measures, (ii) the presence of a possible fifth passenger sitting in the middle of the rear row typical of five-seater cars (please consider that his/her exposure could be different from the other passengers sitting on the rear seats due to limited shielding effect of the front seats), (iii) the effect of side window opening, (iv) the effect of the journey duration. Nonetheless, some practical suggestions can be argued from the scenarios investigated; in particular, we clearly showed that the common-sense norm suggesting that the occupants should sit as far apart as possible in the car (i.e., single passenger sitting on the back seats) can be misleading. Indeed, apart from the front ventilation mode, the passenger sitting on the front seat (close to the driver) presents risk of infections lower than those sitting on the back seats. Thus, since the use of the front window defrosting is mostly required (e.g., to avoid that the humidity in the air condensates on the glass), a mixed ventilation mode (i.e., simultaneous use of front and windshield inlet sections) should be adopted and the passenger should sit close to the driver to receive a lower risk. Besides, mixed ventilation mode is preferred when more than two occupants are sitting in the car, as the windscreen ventilation increases the exposure (and so the dose and the risk) of back-seat occupants. Despite these general suggestions, we point out that generalizing the obtained CFD results to other passenger vehicles could lead to mistakes. Indeed, car cabins comparable in terms of volume and emission rates could present different infection risks for the susceptible occupants as a function of the position of the inlet vents (some cars also have ducts to the rear-seat area), the adjustable angle of inlet air-flow rate, the airflow rate split among the different vents, and the position of the outlet sections (considering that in actual cars the particle exfiltration just relies upon leakages of the cabin): these aspects are here not considered and could be involved in future developments of the study.

Regardless, our results show that CFD is necessary to evaluate the fate of these particles more accurately and that a proper design of the HVAC system (e.g., in terms of positioning of the inlet and outlet vents), in view of significantly reducing the risk of infection, is suitable. This is a key finding since it demonstrates that in indoor environments characterized by fixed seats the risk of infection can be in principle controlled by properly designing the flow patterns of the environment, that is, moving toward an ad hoc personalized ventilation.75,76

4 | CONCLUSIONS

In the study, we proposed and applied an integrated approach combining a validated CFD transient approach and a recently developed predictive emission-to-risk approach to estimate the SARS-CoV-2 Delta variant risk of infection in a car cabin under different conditions in terms of ventilation (ventilation mode and airflow rate of the HVAC system) and emission scenarios (expiratory activity, that is, breathing vs. speaking, and position of the infected subject within the car cabin).

The results of the study clearly showed that the risk of infection, and consequently the probability of secondary cases, is strongly influenced by the ventilation mode, the HVAC flow rate, the position of the infected subject, and the expiratory activity. As an example, in case of driver infected speaking for the entire journey, a reduced ventilation (low flow rate) or a less effective ventilation (e.g., windshield defrosting mode) can cause high risk of infection (>50% for at least one of the passengers) then leading to a high probability (~60%) of at least one secondary case in only 30-min of exposure. The risk of infection is clearly reduced when (i) higher flow rates are adopted as they dilute the virus-laden respiratory droplets emitted by the infected subject or (ii) the infected subject just breathes instead of speaking (for those scenarios the probability that none of the passengers gets infected is >90%). Furthermore, the front ventilation mode evaluated herein provides effective aerodynamic containment between the front and back of the vehicle, meaning passengers sitting in the back seats are better protected from an infected driver relative to mixing ventilation. On the contrary, the windshield defrosting leads to the highest average risk among the passengers; anyway, since the use of front window defrosting is sometimes needed, according to the finding of the CFD analyses, a practical suggestion could be adopting a mixed ventilation mode.

FIGURE 14 Results of Bernoulli trial calculations for Revent and the probability distribution of secondary cases (C) for scenarios under investigation.
The findings of the paper demonstrated that CFD approaches are needed to properly address the individual risk in such confined spaces as the fluid-dynamic conditions significantly affect the airflow patterns and, consequently, the spatial distribution of the virus-laden respiratory particles within the cabin. Thus, simplified zero-dimensional approaches assessing the average risk of the susceptible (not accounting for the specific flow patterns in the confined space), can lead to miscalculation of the risk of the exposed subjects, particularly for ventilation modes not designed for mixing. Indeed, the well-mixed solutions for speaking infected subject here shown are roughly comparable with the CFD ones only in case of very low flow rates (10% of the maximum flow rate), that is, when the reduced airflow rates do not effectively clean the breathing zone of the exposed subjects and the virus-laden concentrations are likely homogenous within the car cabin.

Summarizing, CFD modeling is a valuable tool to produce such recommendations for specific applications, which are not possible with simple zero-dimension models and, even if the CFD results here provided are not directly transferable to other cars (due to the case-specific geometry, vent positions, etc.), the finding here indicates that ad-hoc designing of the airflow of closed environments in view of reducing and controlling the risk of infection is achievable, especially when the spatial locations of the occupants are fixed.

5 | AUTHORS’ STATEMENT
Fausto Arpino: Methodology, Data curation, Writing-Original draft preparation; Giorgio Grossi: Methodology, Formal analysis, Writing-Original draft preparation; Gino Cortellessa: Methodology, Data curation, Writing-Original draft preparation; Alex Mikszewski: Data curation, Formal analysis; Lidia Morawska: Supervision, Writing-Reviewing and Editing; Giorgio Buonanno: Conceptualization, Writing-Reviewing and Editing; Luca Stabile: Methodology, Data curation, Writing-Reviewing and Editing.

CONFLICT OF INTEREST
The authors have no conflicts of interest to declare.

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