How opening windows and other measures decrease virus concentration in a moving car

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Abstract

Purpose – Due to the ongoing Covid-19 pandemic, ventilation in a small cabin where social distancing cannot be guaranteed is extremely important. This study aims to find out the best configuration of open and closed windows in a moving car at varying speeds to improve the ventilation efficiency. The effectiveness of other mitigation measures including face masks, taxi screens and air conditioning (AC) systems are also evaluated.

Design/methodology/approach – Each window is given three opening levels: fully open, half open and fully closed. For a car with four windows, this yields 81 different configurations. The location of virus source is also considered, either emitting from the driver or from the rear seat passenger. Then three different travelling speeds, 5 m/s, 10 m/s and 15 m/s, are examined for the window opening/closing configurations that provide the best ventilation effect. A study into the effectiveness of face masks is realised by adjusting virus injection amounts; and the simulation of taxi screens and AC system simply requires a small modification to the car model.

Findings – The numerical studies identify the top window opening/closing configurations that provide the most efficient ventilation at different moving speeds, along with a comprehensive ranking list. The results show that fully opening all windows is not always the best choice. Simulations evaluating other mitigation measures confirm good effect of face masks and poor performance of taxi screens and AC systems.

Originality/value – This work is the first large-scale numerical simulation and parametric study about different window opening/closing configurations of a moving car. The results provide useful guides for travellers in shared cars to mitigate Covid-19 transmission risks. The findings are helpful to both individuals' health and society's recovery in the Covid-19 era and they also provide useful information to protect people from other respiratory infectious diseases such as influenza.

Keywords Covid-19, Car, Open windows, Computational fluid dynamics, Internal ventilation, Airborne transmission

Paper type Research paper

1. Introduction

The world has suffered from the Covid-19 pandemic since the end of 2019. As of November 2021, 250 million confirmed cases and more than 5 million deaths have been reported according to World Health Organisation's daily updated website, and the numbers are still increasing. As a novel respiratory infectious disease, Covid-19 is similar to such diseases as influenza, severe acute respiratory syndrome (SARS) and Middle East respiratory syndrome (MERS), transmitted directly by the airborne route and indirectly via contact with a contaminated environment (Gudbjartsson *et al.*, 2020; Bai *et al.*, 2020; Yu *et al.*, 2020). Airborne transmission happens in two ways: via large liquid droplets coughed out, or through smaller aerosol spray emitted when coughing or speaking. This makes droplet transmission, aerosol transmission and contact transmission the three main transmission modes of Covid-19 (Domingo *et al.*, 2020).

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On the one hand, Covid-19 has led to millions of people losing their lives, as well as causing potential long-term illness to those who get in contact with the disease (Akkaya *et al.*, 2021; Enghard *et al.*, 2021; Huang *et al.*, 2021). On the other hand, large-scale lockdown and severe travel restrictions adopted all over the world have caused massive damage to the economy and society (Monroy-Torres *et al.*, 2021), in the quality of living, people's mental health (Xiang *et al.*, 2020; Kang *et al.*, 2020; Al-Rahamneh *et al.*, 2021) and even the rise of crime cases (Barasa *et al.*, 2021), etc. To address these problems, a number of countries have set to return to the normal economic and social activities with a high proportion of the population received vaccination. However, with more variants of the virus appearing, the efficiency of vaccines may decline (Lopez Bernal *et al.*, 2021), and humans are increasingly likely to live with the Covid-19 virus for a few more years. Therefore, it is crucial for individuals to take mitigation measures in daily life. One of the most demanding situations is in shared vehicles, since people cannot break away from transportation in their daily routine.

In a shared vehicle, the risk from contact transmission can be easily controlled by hand sanitisation measures (Cheng *et al.*, 2020), and the large droplets are heavy enough to fall onto a surface within a few seconds. However, the virus can circulate in the air for prolonged periods as aerosol (Eissenberg *et al.*, 2020; Qu *et al.*, 2020). Therefore it is vital to improve the ventilation efficiency of vehicles. The most common ways, similar to those in buildings (Park *et al.*, 2021), are opening windows and using air conditioning (AC) or fan systems on the vehicle.

Experiment and numerical simulation are the two main routes to study airflow inside vehicle cabins, and the simulation approach is usually significantly cheaper to realise in terms of both cost and time. Compared to the airflow analysis around a moving vehicle, the study of airflow inside a moving vehicle is quite limited. Kale *et al.* (2007) studied the complex airflow inside a bus with open windows and investigated the air flow speed and pathways. Polanco *et al.* (2009) studied both internal and external air flow patterns of a car with a fixed window configuration and two different moving speeds. Ibrahim and Mehta (2018) analysed effective AC inside the rear passenger area and proposed an air depression design that optimises the air flow and temperature in a small car cabin. Pirouz *et al.* (2021) studied the airflow patterns in three typical vehicles, i.e. car, bus and aeroplane, and evaluated ventilation efficiencies of heating, ventilation and air conditioning (HVAC) systems by air changes per hour (ACH). The results indicate that opening windows can decrease the contamination loads and improve the low ACH provided by the HVAC system. Mathai *et al.* (2021) compared airflow patterns of six different window configurations, and analysed potential disease transmissions between driver and passenger.

Until recently, there has not been a systematic study on the best ventilation measures for a moving car, which is the main objective of this paper. Hence, this study is the first large-scale numerical simulation and parametric study about different window opening/closing configurations of a moving car. In the study, each of the four windows of a moving car is examined for three opening levels: fully open, half open and fully closed. Virus emission can take place at either the front driver or the rear passenger. Three different car speeds are considered: 5 m/s (approximately 11 mph), 10 m/s (approximately 22 mph) and 15 m/s (approximately 34 mph). The effectiveness of other mitigation measures including face masks, taxi screens and AC system are also evaluated.

The remainder of this paper is organised as follows. The model setup is described in section 2. Then, section 3 illustrates all simulations undertaken in the study, where sections 3.1 and 3.2 study the windows efficiency, while sections 3.3, 3.4 and 3.5 study the effectiveness of face covering, taxi screen and AC system respectively. Finally, section 4 summarises the overall conclusions.

2. Model set-up

The continuous development of computational fluid dynamics (CFD) theory and the associated simulation tools and the rapidly growing computing power have made it much easier than ever to analyse complex flow problems in various engineering applications. ANSYS Fluent is one of the most frequently-used CFD software, and it is also the main simulation platform for the aforementioned studies (Ibrahim and Mehta, 2018; Pirouz *et al.*, 2021; Kale *et al.*, 2007). ANSYS Fluent provides comprehensive modelling capacities for a wide range of incompressible and compressible, laminar and turbulent fluid flow problems, and more technical information can be found in its official user's guide. In this study, we also adopt ANSYS Fluent as the simulation tool to investigate the ventilation performance of various mitigation measures to control airborne virus transmission inside a moving car, and the model details are explained in the following subsections.

2.1 Basic calculation model

The car model is 1.8 m in width, 4.5 m in length and 1.2 m in height. Two people are set in the model: the driver is on the front right seat and the passenger is directly behind the driver on the rear seat. Three opening levels are set for each window, which leads to a total of $3^4 = 81$ cases for a typical four-window car. The three levels are fully open, half open and fully closed. To implement this, the geometry of each window is divided into two parts, and a half open window is set to open at the half position of the window height. In the simulation, every part of windows can be modelled as part of the car body or as part of the interior. It is noted that only the internal cabin zone (maximum length is 2.5 m) is set as the fluid flow zone, and other zones including car head, trunk, seats and people bodies are suppressed, as shown in Figure 1.

To simulate movement of the car, it is placed in the centre of a wind tunnel, as shown in Figure 2. For wind tunnel tests in aerospace engineering, it is suggested that aeroplane/aerofoil models should take up no more than 80% the width of the test section (Jaramillo, 2017). Following the physical-test design guide and based on trial simulations, the dimensions of the wind tunnel used in this study are determined as 3.8 m wide, 2.7 m high and 10.5 m long. The car is placed at the centre horizontally with a gap of 0.5 m to the bottom and 1 m to the top vertically. Our test simulations show that for the car speeds up to 15 m/s, using larger wind tunnel has very limited influence on the flow field around the car. Both inlet and outlet of the wind tunnel are controlled by a fixed velocity equal to the car speed, which helps to quickly form a steady flow field.

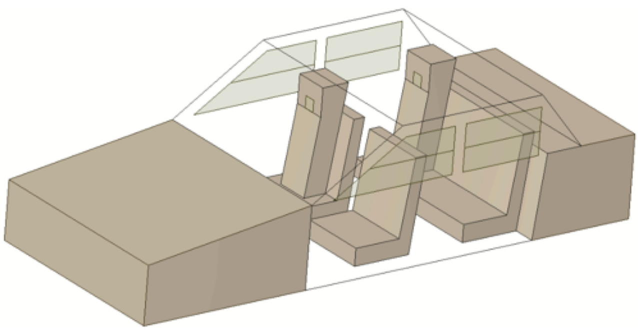


Figure 1.
The car model

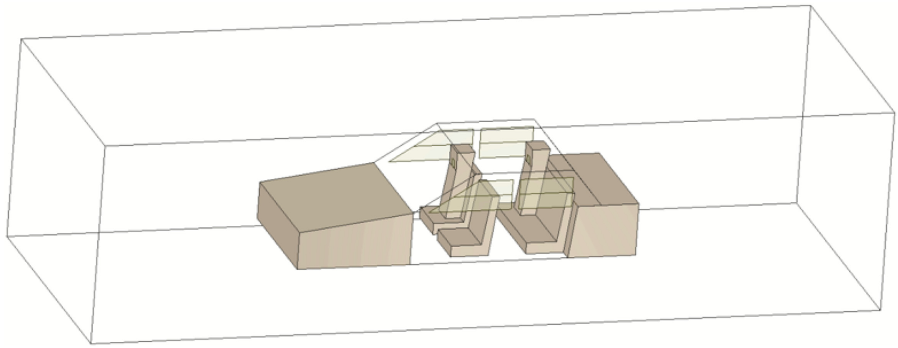


Figure 2.
The calculation model of the car in a wind tunnel

The mouth of each person is simplified as a 0.1 m × 0.1 m square, and the vertical distance from the centre of the mouth to the car roof is 0.85 m. The total number of droplets from a single cough is 110 on average (Chao *et al.*, 2009) and the large droplets are heavy enough to fall down to the floor or a surface relatively quickly. It is the tiny particles that form the aerosol and carry the virus to circulate in the air for longer periods of time. Therefore it makes more sense to track the expelled air from people instead of the coughed droplets. In this study, the expelled air is marked by very small particles with the diameter of 10^{-6} m and density of 10^3 kg m^{-3}, which are small enough to float in the air and almost have no influence to the air flow. In all simulations, we set a single cough lasting 0.5 s with 10,000 air-marker particles injected at a constant rate. The expelled air flow velocity, which equals to the particle injection velocity, is 10 m/s. It is noted that the marker particles described here are not the actual droplets emitted from the cough.

To account for the turbulence effect in the air flow, the standard k-ϵ model is adopted in this study, where the turbulent kinetic energy k and the turbulent energy dissipation rate ϵ are computed using (Versteeg and Malalasekera, 2007)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + 2\mu_t E_{ij}E_{ij} - \rho\epsilon \tag{1}$$

$$\frac{\partial(\rho\epsilon)}{\partial t} + \frac{\partial(\rho\epsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}2\mu_t E_{ij}E_{ij} - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \tag{2}$$

where ρ is the density of the fluid, u_i the velocity component in the corresponding direction, E_{ij} the component of rate of deformation, t the time and x_i, x_j the positions in different dimensions. Prandtl numbers σ_k and σ_ϵ connect the diffusivities of k and ϵ to the eddy viscosity μ_t, which is given by

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \tag{3}$$

The constant parameters C_μ, σ_k, σ_ϵ, $C_{1\epsilon}$ and $C_{2\epsilon}$ in Eq. (1) and Eq. (2) are set as standard values derived from data fitting for a wide range of turbulent flows: $C_\mu = 0.09$, $\sigma_k = 1.00$, $\sigma_\epsilon = 1.30$, $C_{1\epsilon} = 1.44$ and $C_{2\epsilon} = 1.92$ (Versteeg and Malalasekera, 2007).

2.2 Mesh convergence study

The mesh convergence study determines the minimum mesh resolution required in a model to ensure the mesh-independent simulation result, thereby it finds the balance between the accuracy and efficiency requirements. In this study, the ANSYS-generated unstructured

tetrahedral meshes are adopted. Three different mesh schemes are tested, with 266, 916, 296, 869 and 368, 160 elements, respectively. In these tests, the front-right window and the rear-right window are fully open while the other two are fully closed. The car speed is set as 15 m/s, i.e. the upper limit in this study. With the time step of 0.001 s and the total simulation period of 10 s, the final average air flow velocities of the front-right window is 3.71 m/s, 3.61 m/s and 3.58 m/s, respectively. When the element number increases from 296, 869 to 368, 160; the result only changes slightly, with the change rate of less than 1%. Thus, the mesh with 296, 869 elements is adopted for the following simulations. Figure 3 shows the simulation mesh with two section planes.

3. Results and discussion

More than 300 simulations have been carried out in this study. As discussed in Section 2.1, there are 81 cases for a typical four-window car by simplifying the status of each window as fully open, half open or fully closed. First, all these cases with one cough from the driver or the rear-seated passenger are conducted for the constant moving speed of 15 m/s. Then, to avoid unnecessary simulations, only the top 38 configurations (those that provides the best ventilation) of the driver coughing cases are rerun with different moving speeds of 10 m/s and 5 m/s to safely conclude the lists of top five window configurations. Next, the top five window configurations with speeds of 15 m/s, 10 m/s and 5 m/s are simulated with face masks worn, which is modelled by decreasing the number of particles injected. Finally, additional simulations of taxi screens and AC system equipped are performed, which requires a slight modification of the model.

In all simulations, only one cough occurs at the beginning, which lasts 0.5 s with 10,000 marker particles injected at a constant rate from random positions in the mouth zone. The expelled air flow velocity, which equals to the particle injection velocity, is 10 m/s and normal to the mouth surface. The time step of simulation is 0.001 s, and the maximum iterations of each time step is set as 20. After a fixed period of 10 s, the number of remaining marker particles are collected which is denoted as n_{10s}. So the remaining particles ratio after 10 s, r_{10s}, can be calculated by

$$r_{10s} = \frac{n_{10s}}{N} \tag{4}$$

where $N = 10{,}000$ is the total number of injected particles.

3.1 Coughing from different person inside of the car

Virus emission from different locations inside the car needs to be considered. The driver at the front right seat and the passenger at the rear right seat are implemented in the model, while

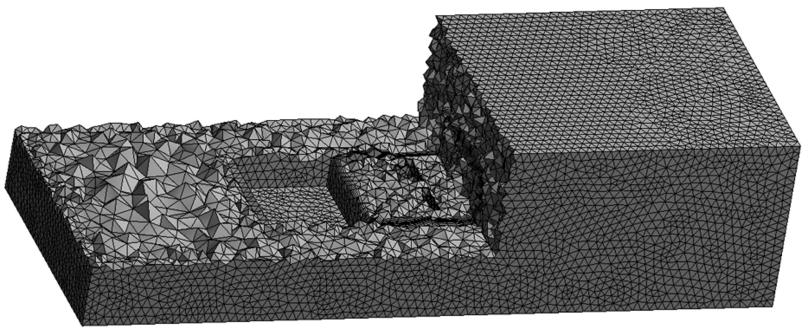


Figure 3.
Mesh of the calculation model

the scenarios of passengers on the front left seat or the rear left seat can be speculated by symmetry. In this section, the two scenarios (a single cough from each person) lead to $81 \times 2 = 162$ cases, which are simulated with the fixed speed of 15 m/s, approximately 34 mph. The remaining particles ratios after 10 s, r_{10s} are recorded and classified into different groups.

For the 81 simulations of driver coughing, the numbers of each range are shown in Table 1. There are 7 cases in the first group, of which the remaining particles after 10 s are less than 10%. A bar graph including detailed information for these 7 cases is shown in Figure 4. The optimal scheme for ventilation is achieved by fully opening the front-right and rear-left windows and closing the front-left and rear-right windows, which gives an r_{10s} value of 3.31%. The window opening/closing configurations are indicated on the graph with the labels of front-left (FL), front-right (FR), rear-left (RL) rear-right (RR). Figure 5 is the bar chart of the second group where $r_{10s} = 10-20\%$. It is worth noting that fully opening all windows is not one of the top configurations, with the percentage of remaining particles being 12.83%, only ranked at the 11th place.

Table 2 includes the results for the other 81 simulations with the rear right passenger coughing and the bar chart of 0–30% groups is shown in Figure 6. The best configuration of the rear person coughing scenario is half opening the FR, FL and RL windows and fully opening the RR window, of which the ratio of remaining particles after 10 s is 19.52%, much greater than that of the best combination of the front person coughing scenario. Again, it is observed that fully opening all windows does not gives the best ventilation, and it only achieves $r_{10s} = 40.26\%$, ranked at 28th out of 81 configurations.

Overall, the contamination from the rear part of the car is much more difficult to clean than that from the front zone. This is because the particles injected in the rear part are more difficult to enter the front-to-back flow field generated by opening windows. Therefore it can be concluded that sitting at the front is generally safer than sitting at the back. With the travelling speed of 15 m/s, the best window configuration to minimise virus concentration

r_{10s}	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100
No.	7	11	10	10	4	10	12	8	5	4

Table 1. Ranking groups of the driver coughing cases

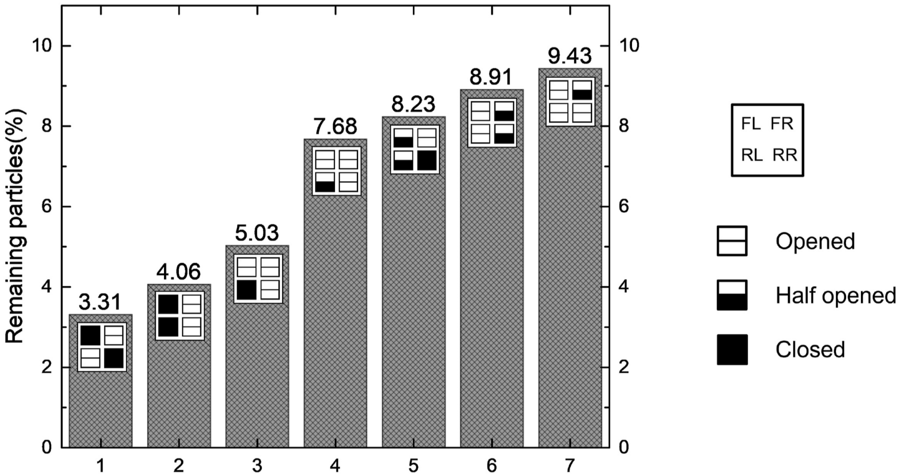


Figure 4. Window configurations for the driver coughing case: 0–10% group

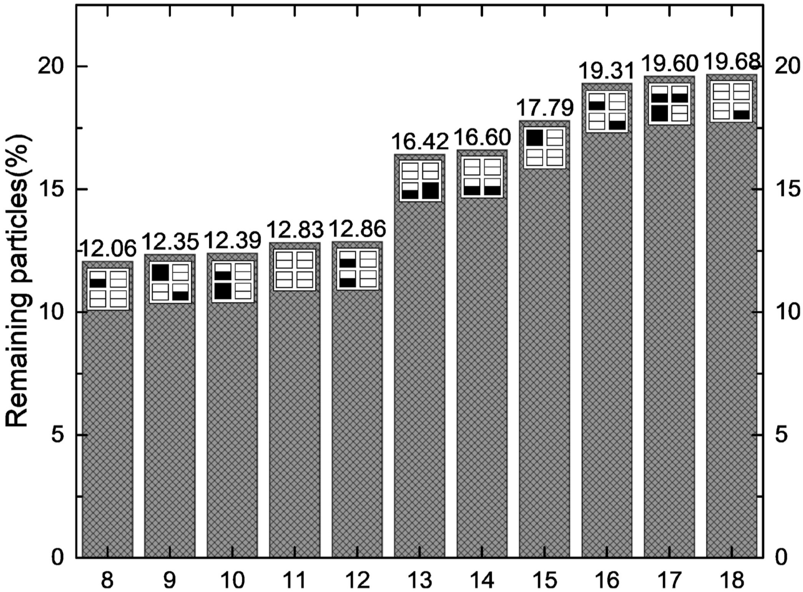


Figure 5.
Window configurations for the driver coughing case: 10–20% group

Table 2.
Ranking groups of the passenger coughing cases

r_{10s}	19.52	20–30	30–40	40–50	50–60	60–70	70–80	80–100
No.	1	8	18	20	14	8	8	4

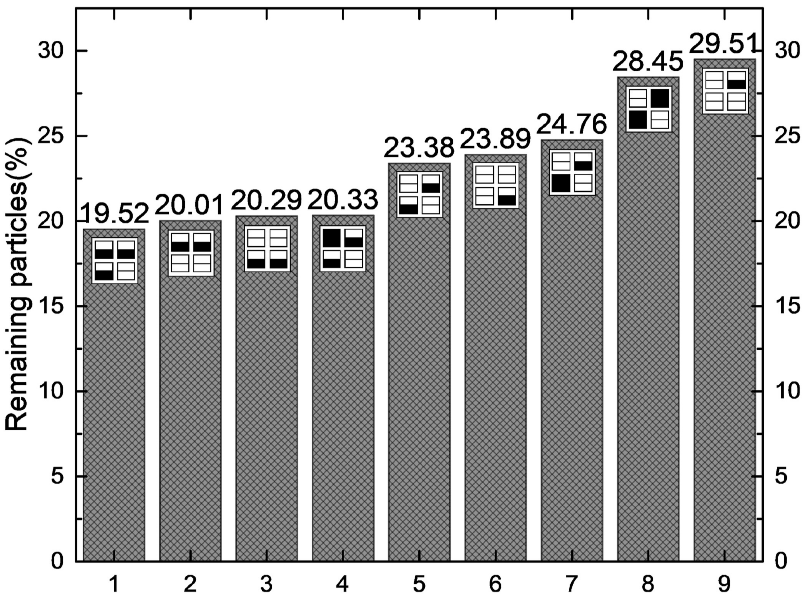


Figure 6.
Window configurations for the rear passenger coughing case: 0–30% group

when the driver is coughing is opening the front window near the coughing person and either one of the rear window. However, when the passenger is coughing, most of the top configurations have all windows open, either half or fully.

The results of all 162 simulations can be found in Appendices Table A1 and A2.

3.2 Comparison of different car speeds

In Section 3.1, all window configurations have been covered. However, the moving speed of a car can change frequently in reality, so it is necessary to investigate the ventilation efficiency for different speeds. The car travelling speed considered in Section 3.1 is 15 m/s, approximately 34 mph. If the car is travelling at higher speeds, it would be no longer suitable to open windows, as this can strongly affect travellers' comfort and even safety. Therefore, another two lower speeds, 5 m/s (approximately 11 mph) and 10 m/s (approximately 22 mph) are examined in this section. Because the air contamination from the rear person is much harder to clean, with the best r_{10s} of only 19.52%, the effect of opening windows would be very poor with a lower speed. So in this section, only the driver coughing scenario is simulated with the two lower speeds. In order to avoid repetitive work, only the top 38 configurations, i.e. those with the r_{10s} lower than 40%, are rerun to safely obtain the top 5 lists.

Tables 3 and 4 list the top 5 window configurations for the speeds of 5 m/s and 10 m/s, respectively. For comparison, the top 5 configurations of 15 m/s are also listed in Table 5. Considering the stop-start nature of urban driving and constant changes of direction, a comprehensive list is given in Table 6 by averaging the results of all three speeds. In the tables, ○ denotes fully open, ◑ half open and ● fully closed.

From Table 6, the best configuration is half opening RL window and fully opening the other three, and the second-best is fully opening all four windows, which are both highly ranked in 5 m/s and 10 m/s lists, according to Tables 3 and 4. Thus, it can be concluded that keeping most of windows open can maximise the ventilation efficiency at lower speed condition, where the pressure difference between inside and outside of the car is far less. While

Rank	Front-Left	Front-Right	Rear-Left	Rear-Right	r_{10s} (%)
1	○	○	◑	◑	46.21
2	○	○	◑	○	50.27
3	◑	○	◑	○	51.84
4	○	○	●	○	51.92
5	○	○	○	○	52.50

Table 3. Top 5 configurations of the driver coughing cases at the car speed 5 m/s

Rank	Front-Left	Front-Right	Rear-Left	Rear-Right	r_{10s} (%)
1	○	○	◑	○	15.70
2	○	○	○	○	16.49
3	◑	○	◑	○	26.55
4	●	○	◑	○	27.98
5	○	○	○	◑	29.68

Table 4. Top 5 configurations of the driver coughing cases at the car speed 10 m/s

at high speed, the pressure difference is large enough, such that only opening one front window and one rear window can help to quickly form a flow-in and flow-out field, and it is more efficient than opening all windows. The data also show the difference in r_{10s} values can be very large for different speeds, e.g. almost 14 times between the best configurations of 5 m/s and 15 m/s lists.

The results of all $38 \times 2 = 76$ simulations can be found in Appendix 2.

3.3 *Effectiveness of face masks*

As of November 2021, face covering is still legally required or strongly recommended on public transport in many countries, e.g. Wales where the authors live. Face coverings not only protect people from infection but also significantly reduce the virus emission if the wearer is an infectious source. In this section, effectiveness of surgical masks is studied. According to the experimental research (Asadi *et al.*, 2020), wearing surgical masks can reduce the outward particles emission rate by 90% on average during speaking or coughing, compared to wearing no mask. So in the simulations, only 10% of injected particles, i.e. 1,000 particles are emitted. The configurations in Tables 3–5 are re-simulated with 10% particle injected. The results are shown in Tables 7–9.

Table 5.
Top 5 configurations of the driver coughing cases at the car speed of 15 m/s

Rank	Front-Left	Front-Right	Rear-Left	Rear-Right	r_{10s} (%)
1	●	○	○	●	3.31
2	●	○	●	○	4.06
3	○	○	●	○	5.03
4	○	○	◑	○	7.68
5	◑	○	◑	●	8.23

Table 6.
Top 5 configurations of the driver coughing cases at the average of three speeds

Rank	Front-Left	Front-Right	Rear-Left	Rear-Right	r_{10s} (%)
1	○	○	◑	○	24.55
2	○	○	○	○	27.27
3	◑	○	◑	○	30.42
4	○	○	◑	◑	31.25
5	○	○	●	○	34.01

Table 7.
Top 5 configurations of the 5 m/s cases with surgical masks

Rank	Front-Left	Front-Right	Rear-Left	Rear-Right	r_{10s} (%)	r_{10s} with masks (%)
1	○	○	◑	◑	46.21	4.66
2	○	○	◑	○	50.27	5.02
3	◑	○	◑	○	51.84	5.18
4	○	○	●	○	51.92	5.20
5	○	○	○	○	52.50	5.25

From Tables 7 and 8, the remaining particles are almost 10 times less with the 10% particles injection in the speeds of 5 m/s and 10 m/s. However, in the 15 m/s scenario, where the remaining particles are already very few, the efficiency of surgical masks is not as good as it is in the low speed conditions, although it is still a good improvement.

3.4 Effectiveness of taxi screens

As of November 2021, wearing a face covering in taxi and private hire vehicles (PHVs) is still mandatory in Wales for passengers, unless they are exempt by special medical reasons. Welsh government guidelines specify that passengers should normally sit in the rear seat of the vehicle, as well as stating that the installation of protective barriers or safety screens is a decision for licencing authorities, PHV operators and firm/individual operating the vehicle to make based on their own assessment of risk (Welsh Government, 2021). Even though screens (also known as partitions) are not legally required, they are actually quite popular amongst taxi drivers and PHV operators all over the world, even prior to the Covid-19 pandemic, as they can help drivers more concentrating on driving to improve safety. There is however no evidence-based conclusion on whether screens help to prevent virus transmission through air. An experimental investigation on the effect of plastic sheeting shielding (PSS) at an office space, shows that extensive use of PSSs create low ventilation rates within PPS-enclosed segments of an office and can result in a false sense of psychological security. PPSs could play positive roles with other simultaneous measures, e.g. opening windows and using fans (Ishigaki *et al.*, 2021). So in this section, screens on a moving car with different window configurations are studied.

As mentioned in the Welsh government report, there are three main types of temporary vehicle screen, as shown in Plate 1 (Welsh Government, 2021). The main difference between the first type, flexible screen and the third one, professionally installed rigid screen, is rigidity as the names indicate. But this makes no difference in the simulation, so they are put into one category and named “big screen”, which leaves no gaps except for the bottom area of the seat. As shown in Plate 1, the second type of screen “rigid screen” leaves large gaps around all edges, which is named as “small screen” in consequence.

Rank	Front-Left	Front-Right	Rear-Left	Rear-Right	r_{10s} (%)	r_{10s} with masks (%)
1	○	○	◑	○	15.70	1.54
2	○	○	○	○	16.49	1.65
3	◑	○	◑	○	26.55	2.66
4	●	○	◑	○	27.98	2.79
5	○	○	○	◑	29.68	2.98

Table 8.
Top 5 configurations of the 10 m/s cases with surgical masks

Rank	Front-Left	Front-Right	Rear-Left	Rear-Right	r_{10s} (%)	r_{10s} with masks (%)
1	●	○	○	●	3.31	0.82
2	●	○	●	○	4.06	1.46
3	○	○	●	○	5.03	1.69
4	○	○	◑	○	7.68	0.95
5	◑	○	◑	●	8.23	1.41

Table 9.
Top 5 configurations of the 15 m/s cases with surgical masks

In the simulations, the size of the small screen is 1.6 m × 0.6 m, and the gap around the left, top and right edges is 0.1 m wide, as shown in Figure 7. As shown in Figure 8, the big screen, with the size of 1.8 m × 1.0 m, only leaves a gap of 0.2 m wide in the bottom edge. The thickness of both screens is ignored and the screen is fixed at the rear edge of the front window.

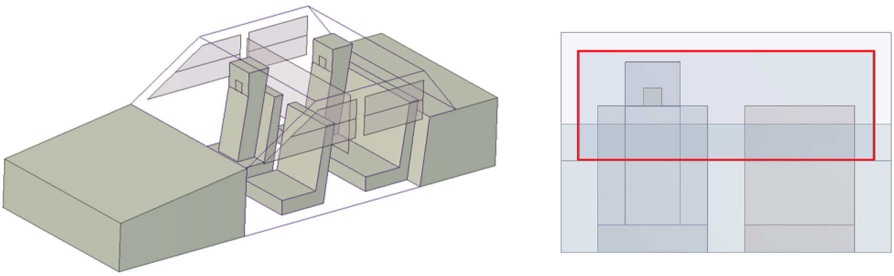
In order to control the simulation work, the half open window status is not included in this round of simulations. With two statuses of each window, fully open or closed, there are $2^4 = 16$ combinations for a four-window car. Considering the three different screen situations, big screen, small screen or no screen, it leads to $16 \times 3 = 48$ cases. As concluded in Section 3.1, airborne contamination from the rear-seated passenger is difficult to be cleaned by opening windows, so the screen effectiveness study is focussed on whether the driver would be safer with the help of screens when the passenger is coughing. The car speed is set as 10 m/s.

Flexible screen
(a)

Rigid screen
(b)

Professionally installed rigid screen
(c)

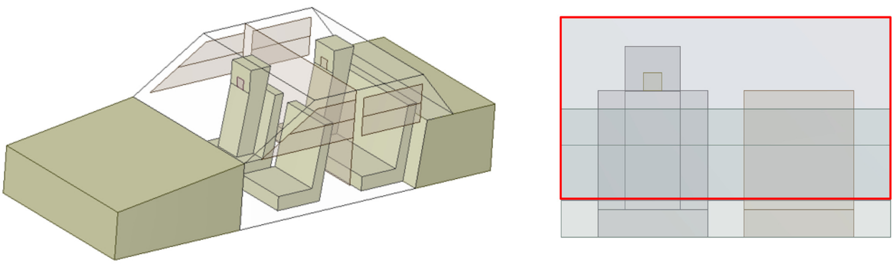
Plate 1.
Three main types of partition screens



Overall view
(a)

Front view
(b)

Figure 7.
A car with small screen



Overall view
(a)

Front view
(b)

Figure 8.
A car with big screen

After 10 s of ventilation, the position of every remaining marker particle is recorded. As shown in Figure 9, the number of particles escaped, remaining in front zone and remaining in rear zone are counted, and they are denoted as $n_{escaped}$, n_{front} and n_{rear}, respectively. The corresponding particles ratios, $r_{escaped}$, r_{front} and r_{rear}, can be calculated by

$$r_{escaped} = \frac{n_{escaped}}{N} \tag{5}$$

$$r_{front} = \frac{n_{front}}{N} \tag{6}$$

$$r_{rear} = \frac{n_{rear}}{N} \tag{7}$$

where $N = 10{,}000$ is the total number of injected particles.

The simulation results are listed in Table 10. For convenience of analysis, Figure 10 shows the results of cases 1–4 in the form of pie charts, where both front windows are closed.

In these four cases, the big screen greatly decreases the particles in the front zone, which is significant for protecting the driver. The Case 2 (only opening the rear-right window) has the lowest proportion of particles left in the front zone, with 5.62%. However, Case 1 (opening both rear windows) is the first suggested configuration for the big screen users, as it provides significant ventilation in both the front and rear zones of the car. It is interesting that in Case 4, closing all windows, which may apply to the high-speed condition and rainy moments, the big screen could reduce the front zone particles by 83.78% compared to the car without screen in 10 s. However, it could be foreseen that the particles would gradually flow into the driving zone as time goes on since all the windows are closed. So in this situation, it is highly encouraged to intermittently open windows for air circulation.

For other cases, it is difficult to conclude whether the screens work well. The big screen certainly has better performance on protecting the driver than the small one in general, while for Case 9 (only closing the front-left window) small screen has a very good ventilation effect in both the front and rear zones.

Big screen and small screen both have some good and bad effects, depending on the specific window opening/closing configurations and travelling speeds. Due to the uncertainty of passenger preference and behaviour, it is hard to guarantee a fixed window opening/closing pattern. Thus, it makes sense to check the average numbers for an overall evaluation. In the averaged case, the big screen can only decrease the front zone ratio by 3.37% and even lead to a great rise in the rear zone ratio by 14.85%, which would subsequently increase virus exposure for successive passengers. The small screen also has negative effect in both the front zone and the rear zone in terms of the remaining particles numbers. This increased contamination caused by poorer ventilation associated to the big and small partition screens is made worse by the increased risk of contact transmission due to the newly-created screen surfaces. Hence, we conclude that adding

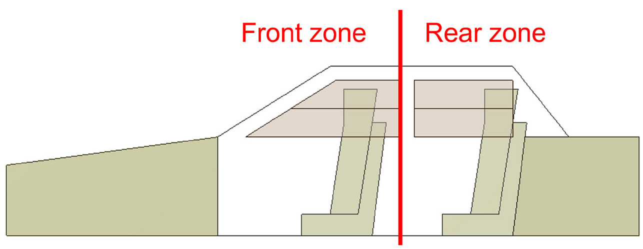


Figure 9.
Front zone and rear zone divided by screens

Table 10.
Simulation results of cars with screens

No.	Window				No screen			Small screen			Big screen		
	Front-Left	Front-Right	Rear-Left	Rear-Right	$r_{escaped}$ (%)	r_{front} (%)	r_{rear} (%)	$r_{escaped}$ (%)	r_{front} (%)	r_{rear} (%)	$r_{escaped}$ (%)	r_{front} (%)	r_{rear} (%)
1	●	●	○	○	54.25	18.29	27.46	49.64	28.28	22.08	68.22	9.27	22.51
2	●	●	●	○	60.24	24.80	14.96	60.97	22.12	16.91	47.00	5.62	47.38
3	●	●	○	●	39.60	22.75	37.65	29.73	41.43	28.84	43.45	10.17	46.38
4	●	●	●	●	0.00	52.65	47.35	0.00	47.51	52.49	0.00	8.54	91.46
5	○	●	○	○	35.36	31.94	32.70	25.60	26.38	48.02	28.40	43.71	27.89
6	○	●	●	○	38.63	24.19	37.18	36.06	20.53	43.41	30.85	31.24	37.91
7	○	●	○	●	35.43	40.13	24.44	27.92	50.83	21.25	26.78	48.59	24.63
8	○	●	●	●	38.26	24.49	37.25	18.90	61.47	19.63	0.07	24.92	75.01
9	●	○	○	○	58.23	21.34	20.43	75.61	12.08	12.31	62.36	18.83	18.81
10	●	○	●	○	52.95	24.97	22.08	36.12	34.91	28.97	47.04	19.95	33.01
11	●	○	○	●	50.90	25.10	24.00	55.47	15.96	28.57	51.51	22.91	25.58
12	●	○	●	●	28.75	31.65	39.60	4.48	56.97	38.55	0.91	29.38	69.71
13	○	○	○	○	77.01	10.69	12.30	64.95	18.12	16.93	53.08	24.41	22.51
14	○	○	●	○	58.05	25.20	16.75	57.64	17.19	25.17	37.06	29.00	33.94
15	○	○	○	●	56.13	23.42	20.45	61.22	21.54	17.24	48.18	29.82	22.00
16	○	○	●	●	46.07	31.76	22.17	24.13	56.97	18.90	1.22	23.11	75.67
Average					45.62	27.09	27.30	39.28	33.27	27.45	34.13	23.72	42.15

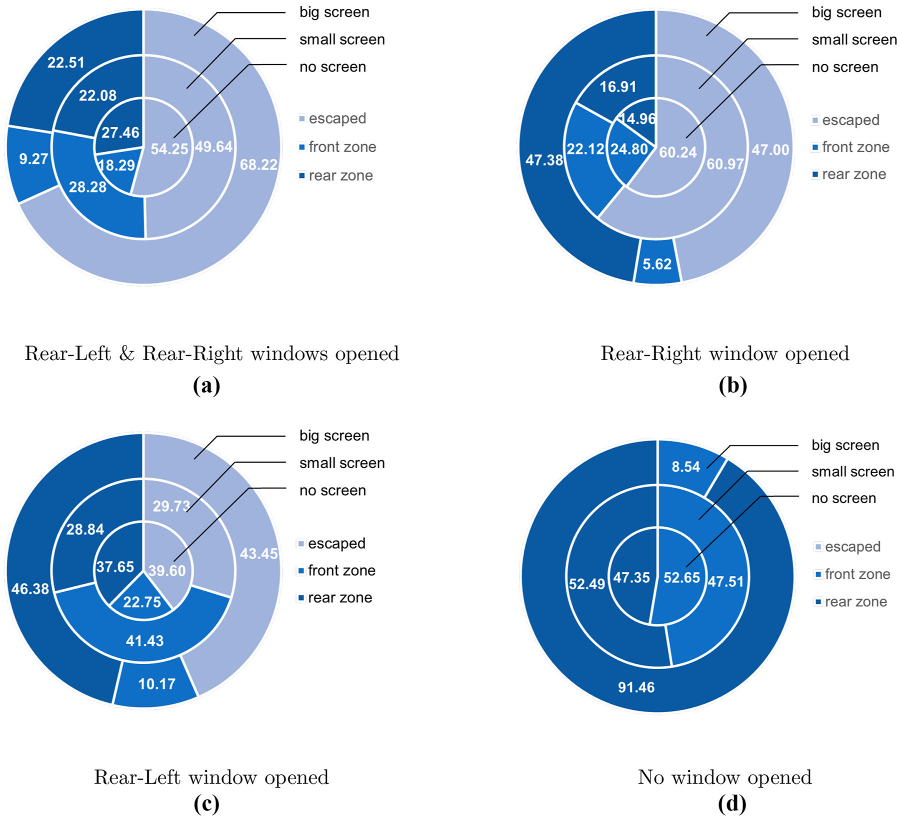


Figure 10.
Pie charts of 4 window configurations results

partition screens, either big or small, is not an effective measure to reduce airborne virus transmission in taxi cars.

3.5 Effectiveness of AC system

As discussed in Section 1, the air flow pattern of a vehicle with the help of fan, AC, HVAC systems, etc. have been extensively studies (Ibrahim and Mehta, 2018; Pirouz *et al.*, 2021). Pirouz *et al.* (2021) pointed out the low air change rate by HVAC system in a car. In this section, we examine the effectiveness of AC system in preventing airborne virus transmission in a moving car.

Several minor changes are made on the original model, as shown in Figure 11, where only shell of the cabin is plotted. The inlet of AC system is simplified as a 600 mm × 100 mm rectangle on the vertical panel in front of the front-left seat. For air circulation, every car has a few passive vents. While the sizes and locations of these vents may differ slightly dependent on the car model, we set a 600 mm × 50 mm vent and two 300 mm × 50 mm vents on the windshield and rear parts of both side panels, respectively.

In the simulation, the air velocity of the AC system inlet is 2 m/s and the thermal change raised by AC system is ignored. The three passive vents are set as interior, i.e. they are not controlled by any velocity or pressure. With all four windows closed and the car's moving speed of 15 m/s, the r_{10s} is 98.70%, i.e. only 1.30% of the particles escaped from the car cabin in 10 s with the effect of AC system.

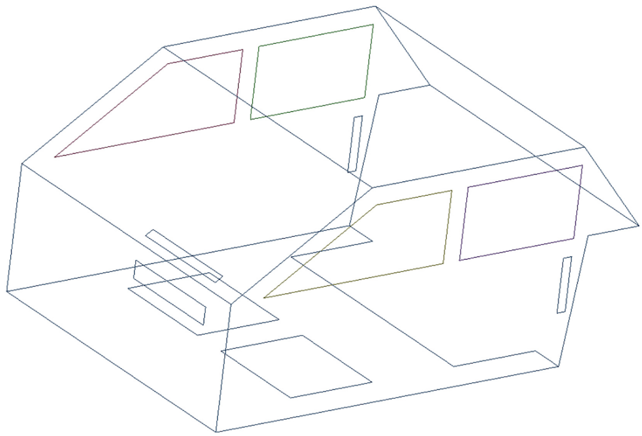


Figure 11.
Simplified view of the car cabin with AC system

In conclusion, there is no doubt that the AC system is important for travellers' thermal comfort and even basic ventilation requirement; however, its ventilation efficiency is too weak to protect people from airborne virus infection.

4. Conclusions

The effectiveness of different methods for reducing the spread of Covid-19 in a moving car is systematically investigated by using CFD simulations. The mitigation measures include opening windows, wearing face mask, installing partition screen and using the AC system. The simulation results show that virus generated by front-seated travellers is 5–10 times easier to be discharged by opening windows than that generated by rear-seated travellers. Thus, providing effective window ventilation is applied, the front seats are generally safer than the rear seats in a shared car. The ventilation effect also depends greatly on the window opening/closing configuration and the travelling speed. To investigate these two factors, we fix the virus load at the front of the car. The results show that at the higher moving speed, i.e. over 15 m/s (approximately 34 mph), the best ventilation is achieved by opening one front window and one rear window, and in this case the virus concentration is reduced by around 95% following a 10 s ventilation. In city driving conditions, i.e. at varying speeds below 15 m/s (approximately 34 mph), it is found that having all four windows open is most beneficial, which reduces the virus concentration by around 75% following a 10 s ventilation. The window ventilation is so effective that it is only necessary to apply it for 10 s at a time, every 5–10 min or whenever somebody coughs or sneezes. Besides opening windows, face covering also has great efficiency for controlling the virus concentration: wearing a surgical face mask will cut the virus concentration by 90%. Other measures including taxi screens and AC system however have poor effect in virus concentration reduction. These research findings provide useful guide to fight the Covid-19 pandemic as well as other future respiratory infectious diseases.

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Appendices

The Appendixes files are available online for this article.

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