



The air we breathe in a car

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Your typical commute hides complex fluid-dynamical pathways of disease transmission. Where you sit and the windows you open could heighten or suppress the risk of airborne infection.

In the single breath you take while reading this sentence, you have inhaled air that once passed through the lungs of everyone who has ever lived before us. That fact is a reminder of the astonishing ability of fluids such as air to spread and disperse the particles they carry. During the COVID-19 pandemic, we're all aware of the possibility of disease transmission through the air. Even so, the number of airborne, or aerosolized, particles that we exchange during social interactions is relatively small if we are in a well-mixed outdoor setting.

In a confined, poorly ventilated space, it's a different story. Respiratory diseases are transmitted primarily indoors, via the turbulent, multiphase clouds of air and droplets spewed when a person coughs, sneezes, or talks loudly (see the Quick Study by Stephane Poulain and Lydia Bourouiba, *PHYSICS TODAY*, May 2019, page 70). Even normal breathing can release up to a thousand airborne particles per liter of air exhaled. And those microdroplets can remain suspended for several minutes before evaporating or settling on a surface. The invisible, buoyant, thermal plumes ever present around us can also carry them far and wide.

That's especially concerning for those of us who commute to work in a passenger vehicle with someone outside our household, such as in a taxi or as part of a carpool. The setting can be considered the epitome of a close, social interaction. With a typical car interior's volume being four cubic meters—a tenth the size of a bedroom—social distancing is impossible.

Cabin microclimate

Most megacities host more than a million ride shares every day, with a median ride duration of about 15 minutes. Not surprisingly, taxis and ride-share companies worldwide have had to implement various mitigation measures, ranging from mask mandates and barrier shields to hand sanitizing. Such measures, however, are only partially effective against airborne particles. Even when a person wears a mask, aerosols can seep through the smallest of gaps between the fabric and their face; they can also travel well beyond the six-foot distance we're told to maintain from others. Within minutes, the tiny microdroplets can pervade the cabin space and expose passengers to a dose of virions.

The critical number and the critical exposure time remain unclear and are likely variables that are dependent on several biological, behavioral, and environmental factors. Can we pos-

sibly know the risk of airborne infection when sharing a car ride with a stranger? In the simplest approximation, cabin air quality—expressed in terms of the number of air changes per hour (ACH)—provides one metric. A more relevant measure would also include the number of passengers. The Centers for Disease Control and Prevention recommend a ventilation rate of at least 10 L/s per person.

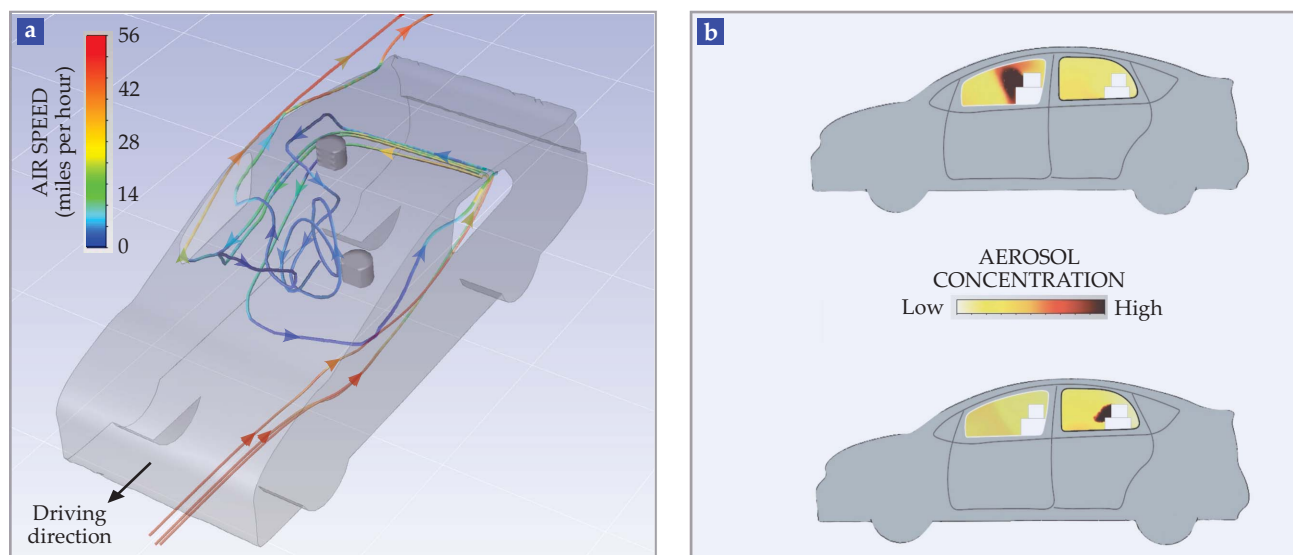
But what's also important for risk assessment are the specific air-flow patterns that become established when the air conditioning is turned on or windows are rolled down. To that end, I worked with colleagues Asimanshu Das, Jeff Bailey, and Kenny Breuer this past year to make sense of the fluid-dynamical pathways that exist inside a passenger car.

We were not the first. Other researchers have looked at those flow patterns—most commonly, to determine how to reduce cabin noise or to see how cigarette smoke dilutes. For our study, the first insights came from Breuer. He realized that when air flows around a car, it sets up pressure on the side windows that is lower in the front than in the rear. Fluid mechanics have been aware of the effect since the 18th century, when Daniel Bernoulli deduced that pressure generally decreases when flow speed increases. If that's the case, we wondered, would the pressure gradient between rear and front windows also cause a rear-to-front air current inside the cabin if the windows are opened?

Field tests that combined smoke visualizations and a flow-wand technique in a moving vehicle bore out that hypothesis. To answer the more detailed questions about the interior air-flow and the transport of potentially infectious aerosols, we turned to computer simulations. In particular, we solved a simplified (time-averaged) version of the Navier–Stokes equations, the same ones that govern the movement of almost all fluids around us.

Airflow patterns

We loosely based the car's exterior geometry on a Toyota Prius driven with a passenger in the rear-right seat. In this two-occupant configuration, we simulated several open and closed window combinations at a driving speed of 50 miles an hour. As expected, the best scenario was to open all four windows, which allows fresh air to enter the rear windows, circulate inside the cabin, and exit through the front windows. The upshot: an effective air exchange rate of 250 ACH, or 50 L/s per person. Were the car's speed cut in half, the exchange rate would also



COMPUTER SIMULATIONS of airflow patterns and aerosol concentrations inside a passenger car driven at 50 miles per hour with front-right and rear-left windows open. **(a)** An air stream (colored lines) enters the cabin through the rear-left window. It then flows across the back seat, turns sharply around the rear-right corner behind the passenger, and exits through the front-right window. A small fraction of the incoming air also circulates inside the cabin before leaving. **(b)** Cross sections of the car show a concentration of aerosols in the cabin that correspond to the driving configuration in panel a. At top is the concentration released by the driver, only a small fraction of which reaches the passenger. The fraction of aerosols released by the passenger (bottom) and reaching the driver is also small. (Image by Varghese Mathai.)

be roughly halved. In either case, the values are well above the ventilation rates recommended in the literature. Clearly, though, the discomfort of cold, hot, or wet air blowing on passengers during poor weather prevents such a drastic approach.

Fortunately, we found a few alternate configurations that provide a more practical compromise. For instance, opening only two windows—one in the rear, the other in the front—produces a cross-ventilation path from the rear to the front of the cabin. Surprisingly, we noticed a few key benefits to opening windows farthest from the two occupants, namely, the front-right and rear-left windows. That configuration, shown in panel a of the figure, creates an air current that enters the cabin from the rear-left window, moves past the back-seat passenger, and exits through the front-right window. Most of the incoming fresh air turns sharply at the rear-right corner, with a little of it circulating in the cabin.

To our surprise, we noticed an airflow barrier established between the occupants. The barrier flow shields the occupants from cross contamination, in much the same way that an air curtain prevents outside air from mixing with indoor air at a controlled temperature in the doorways of supermarkets and shopping malls. That airflow should also reduce the discomfort of fast-moving air blowing directly on the occupants and yet still ensure a good air exchange rate of 150 ACH—about 30 L/s per person.

Particles smaller than 10 μm in diameter follow that air path; they also get diluted by the incoming air stream. After accounting for the two effects—advection and turbulent diffusion—in our simulations, we found that about 5% of the aerosols exhaled by either occupant reaches the other, as shown in panel b of the figure.

Should you now feel safe hailing a ride share? To answer

that question, one must consider not only the physical separation and ventilation rate, but also the actual duration of the ride. For a novel pathogen such as SARS-CoV-2, which is continuing to evolve even as vaccines are taking effect, we can only assess the relative risks. In fact, scientists may have initially underestimated the immense biological variability in the infectivity of people. COVID-19 appears to be a disease wherein the top 20% most infectious people produce 80% of all infections. With those issues in mind, the picture I present is a comparative one. To be wise, we cannot yet breathe a sigh of relief.

Additional resources

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- P. A. Jensen et al., “Guidelines for preventing the transmission of *Mycobacterium tuberculosis* in health-care settings,” *Morb. Mortal. Wkly. Rep.* **54**(RR17), 1 (2005).
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