Parking under the sun: Solar heating as a strategy for passively disinfecting COVID-19 in passenger vehicles during warm-hot weather

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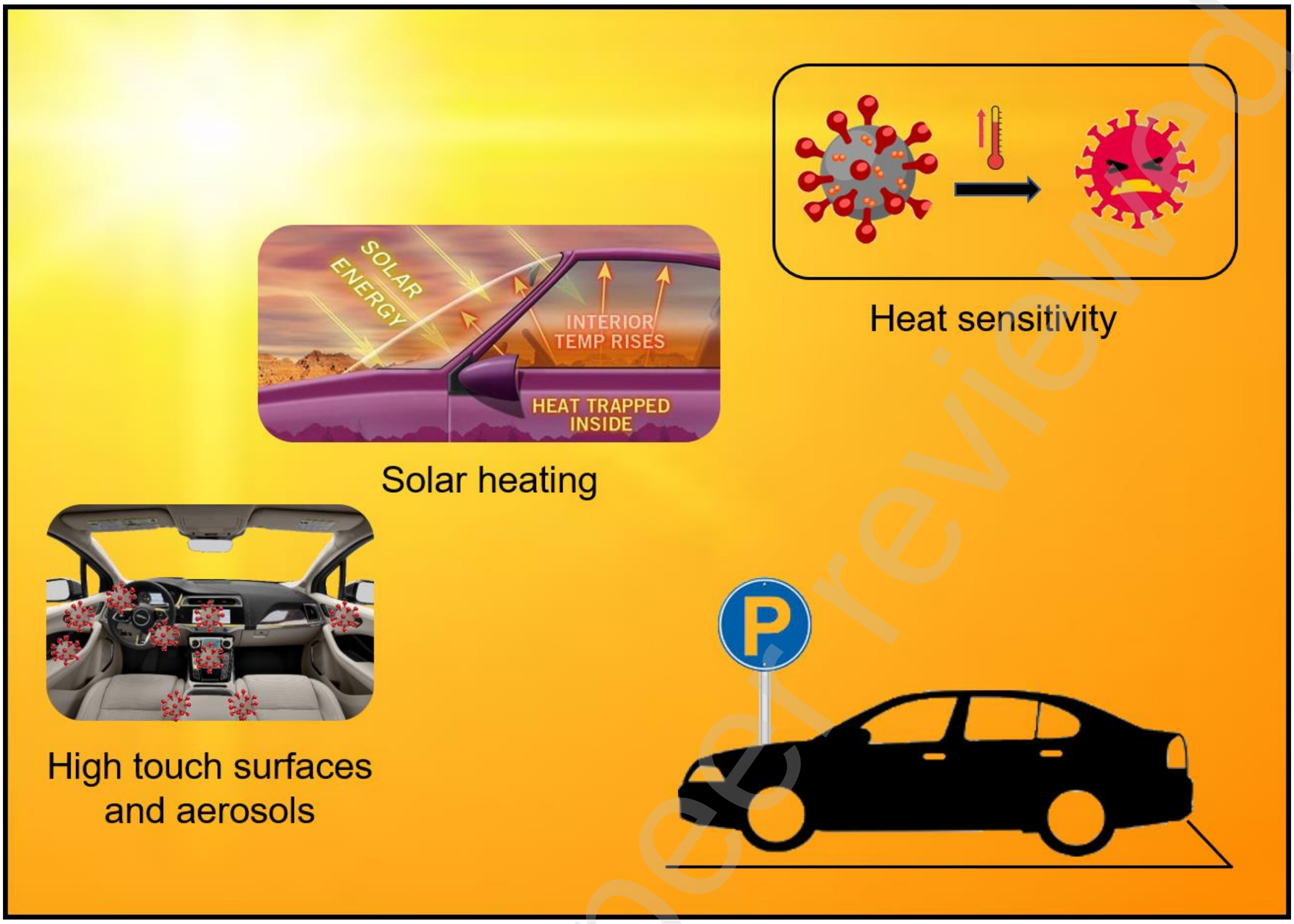
Abstract

Shared passenger vehicles (taxis, Uber, other drivers-for-hire services) are common in daily transportation. The confined, enclosed space as well as commonly touched surfaces in those sub-environments pose elevated risks of COVID-19 transmission via respiratory, contact, and airborne routes. Current regulatory guidelines rely on voluntary acts from passengers on wearing face coverings while require cleaning and disinfecting by drivers, with gaps left between drivers' shifts and transmission from non-symptomatic individuals. A labor-intensive procedure, repetitive manual cleaning and disinfecting may present a nuisance for some drivers and can be ineffective in areas that are difficult to access. There is an urgent need to evaluate other strategies to mitigate the risks of COVID-19 infection in passenger vehicles. Since the persistence of the novel coronavirus is sensitive to ambient temperatures, and that inactivation could be achieved within minutes to half an hour at 50–60 °C, solar heating – by parking vehicles under direct sunlight with doors and windows closed – presents a viable strategy for passively disinfecting COVID-19 in vehicle interiors during warm-to-hot weather. To demonstrate this approach, we measured the temperatures in a white compact-size sedan left in a parking lot under direct sunlight. Air temperatures increased rapidly in the cabin during the first 30–40 min, followed by steady increases in the next hour, then plateaued after reaching 52–57 °C at 90 min. Spatial variations (5 ± 1 °C) were found at four diagonal points in the front and back seat at the breathing and knee heights of an average seated adult, with higher temperatures registered in the front and the upper zone. The results supported our hypothesis that hot air generated by solar heating in enclosed objects provides a viable means of thermal inactivation for COVID-19, in a passive manner that does not involve chemical use, laborious work, or waste discharge to surrounding environments.

Keywords: Coronavirus; SARS-CoV-2; inactivation; sunlight; thermal; heat


Heat sensitivity
SOLAR ENERGY
INTERIOR TEMP RISES
HEAT TRAPPED INSIDE
Solar heating
High touch surfaces and aerosols
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Highlights

- Confined, enclosed space and frequently touched surfaces in many passenger vehicles
- Elevated risks of COVID-19 transmission via respiratory, contact, or airborne route
- Parking under the sun in warm-hot weather allows thermal inactivation of COVID-19
- A passive method requiring no chemical use, manual cleaning, or waste discharge
- Potential for disinfecting automobiles, aircrafts, cruise ships, shipping containers

1. Introduction

1.1 Evidence and risks of COVID-19 transmission in passenger vehicles

Respiratory droplets and contact surfaces have been recognized as the two primary routes of virus spread during the COVID-19 pandemic (WHO, 2020a). In enclosed spaces with inadequate ventilation, airborne transmission may also occur through tiny droplets and particles in air (CDC, 2020a). The confined, enclosed space and frequently touched surfaces in passenger vehicles can become high-risk areas of virus transmission during the current pandemic, particularly in those used for shared transportation services such as taxis, rideshares, other drivers-for-hire vehicles, as well as secondhand vehicles bought and sold between users (Statista, 2020). There have been a number of reports on COVID-19 infections involving passenger vehicles. On 28 January 2020, a 51-year-old Thai taxi driver was confirmed of COVID-19 infection. Potentially acquired from tourists, it became one of the earliest cases of suspected human-to-human transmission of the novel coronavirus (Pongpirul et al., 2020). As of 12 April 2020, a total of 302 taxi drivers in Tehran, the capital of Iran, were infected by COVID-19 (Hu, 2020). Data from the Office for National Statistics (UK) showed that aged-standardized mortality rates involving COVID-19 were significantly higher among taxi drivers and chauffeurs than people in other occupations in England and Wales (ONS, 2020).

Passenger vehicles have limited interior spaces, typically about 100 cubic feet (*ca.* 2.8 m^3), with good sealing of airflows for thermal comfort and quietness inside the cabin (Allen et al., 2020). The enclosed and confined spaces used by different individuals in shared passenger vehicles can elevate the risks of virus transmission via respiratory and contact routes, particularly from pre-symptomatic and asymptomatic individuals (Huff and Singh, 2020). In a recent commentary with signatories of

237 scientists, Morawska and Milton (2020) pointed out that airborne transmission may occur by microdroplets in human exhalation that can linger in air and pose risks of exposure beyond 1–2 m distance from the source. Ho et al. (2020) measured the concentrations of submicron-sized droplets from human respiration within 1.0-m distance of 211 adults, including 205 confirmed cases of influenza and six suspected cases of COVID-19, in a subcompact-size sedan with windows closed and air conditioner in operation using outside air. When no mask was worn, the mean number concentration of particles within the size range of 20–1000 nm ($NC_{0.02–1}$) in cabin air (122,182 ± 79,554 particles/cm^3) were about five times that of the background (22,874 ± 6,998 particles/cm^3). Notably, the study also found a 1–2 time increase of particle concentrations from the background when the person in presence worn a medical or cotton face mask, suggesting common leakages of human respiration from those types of face coverings. In an opinion article (Allen et al., 2020), academics at four U.S. institutions advised the public on the risk of aerosols in passenger vehicles, and advocated riders to keep at least one window open at 3 inches (*ca.* 76 mm) as a safety measure in the current pandemic to prevent aerosol accumulation inside the cabin. Transmission may also occur via contact the commonly touched surfaces in passenger vehicles. These include door handles, windows and window adjusters, seatbelts and buckles, seat adjusters, and other interior parts and surfaces within passengers' reach. In an earlier study, Li et al. (2016) collected samples from taxis in a northeastern city in China and found excessive bacterial contamination in 46.7% of the surface samples and 39.2% of the air samples, with even higher rates detected during rush hours. The study also found that the numbers of bacteria identified in taxi samples were significantly higher than those present in samples from buses, possibly due to their small interior spaces and high occupancy rates.

1.2 Current policies, guidelines, and gaps

During COVID-19, the World Health Organization (WHO) and Centers for Disease Control and Prevention (CDC) in the U.S. advise the public to wear masks when physical distancing is difficult to maintain, such as when using public transport, in shops or other enclosed spaces, including riding in a car with people outside the household (WHO, 2020b; CDC, 2020b). In the EU, passengers were advised to wear face masks in transport hubs and vehicles used for collective transport (EU, 2020). The CDC recommended drivers of rideshare, taxi, limo, or other driver-for-hire vehicles to wear face coverings, and passengers were asked to wear a cloth face covering and cover their mouth and nose with tissues when cough or sneeze and disposed of the tissues after exiting the vehicle (CDC, 2020c). Few law enforcements have been put in place to mandate such requirements, particularly on passengers. In the UK, law enforcement was recently introduced in Wales for people to wear face coverings on taxis, buses, and other public transport (Wales, 2020). Starting from July 2020, Uber requires its drivers and passengers in the U.S. and Canada to wear a mask or face covering (Brown, 2020). Didi, the largest app-based car-hailing platform in China, also implemented mandatory requirements on drivers to wear masks whenever they are in service, and drivers are permitted to refuse passengers who do not wear masks (Didi, 2020).

The CDC recommended that commonly touched surfaces in non-emergency transport vehicles, including passenger vans, accessible vans, and cars for transportation to receive medical care, should be cleaned with detergent or soap and water, and then disinfected with EPA-registered antimicrobial products or alcohol solutions with at least 70% alcohol (CDC, 2020d). The U.S. public health agency advised drivers to, as a minimum, perform these procedures at the beginning and end of each shift and between transporting passengers who are visibly sick (CDC, 2020d). CarMax, the largest secondhand car trading platform in the U.S., requires disinfection of high-touch surfaces in vehicles traded through the platform during COVID-19 (Carmax, 2020). Guazi.com, a popular web portal for buying and selling used cars in China, offered “online contactless car purchase” and required medical-grade ozone and ultraviolet disinfection in vehicles traded on the website (Wang, 2020).

Major gaps, however, exist in current policies and regulatory guidelines on preventing virus transmission in shared transportation vehicles. To begin with, in most places there are no mandatory requirements on wearing masks or face coverings for passengers using taxis, private hire vehicles, or sharing vehicles with members outside their households. Such acts would rely on precautions and voluntary acts taken by passengers themselves. Given that commuters constitute the vast majority of people in taxis or other for-hire passenger vehicles, risks remain on the transmission of viruses via respiratory exposure to droplets and aerosols in those confined environments, even if the drivers are required to wear masks or face coverings throughout their services. Meanwhile, the lack of cleaning and disinfecting between drivers’ shifts could expose passengers to virus-contaminated contact surfaces inside the vehicle after being touched by asymptomatic or pre-symptomatic individuals. Further, the complex structure of vehicle interiors and passengers with different habits and behaviors, including children, mean that gaps would inevitably exist on some touched spots that can be easily overlooked during the routine cleaning and disinfecting. Lastly, the use of chemical disinfectants and the cleaning procedures required both before and after demand time-consuming and labor-intensive manual work, which may present a nuisance for some drivers.

1.3 Room-temperature persistence and thermal sensitivity of SARS-CoV-2

The causation agent of the COVID-19 pandemic, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), exhibited prolonged persistence on aerosols and surfaces under room temperature. van Doremalen et al. (2020) first showed that, at 21–23 °C and a relative humidity (RH) of 65%, SARS-CoV-2 remained viable for at least 3 h on aerosol particles. In a more recent study, Fears et al. (2020) also found that SARS-CoV-2 maintained virion integrity and infectivity for up to 16 h on respirable-sized aerosols under similar conditions (21–25 °C and 42%–64% RH). SARS-CoV-2 and other coronaviruses could survive several days on materials similar to those frequently touched surfaces in passenger vehicles. Riddell et al. (2020) showed that at 20 °C and 50% RH, SARS-CoV-2 maintained infectivity for at least 28 days on common surfaces such as glass and stainless steel, which far exceeded the previous findings on the persistence of SARS-CoV-2 on these surfaces under similar conditions (22 °C and 65% RH) (Chin et al., 2020). Chan et al. (2020) further showed that, in a dry state, SARS-CoV-2 maintained viability on glass surfaces for 3–4 days under room temperature (22–25 °C). Although there is a lack of data on the viability of SARS-CoV-2 on environmental surfaces in real-life settings, other coronaviruses, including the SARS-CoV-1 which shares 79.6% of its genome sequences with the novel coronavirus, have shown prolonged survival under various environments in a number of studies (Aboubakr et al., 2020).

While SARS-CoV-2 exhibited prolonged survival on aerosols and various types of surfaces under room temperature, it showed high thermal sensitivity, with fast inactivation observed under elevated temperatures. Chin et al. (2020) incubated SARS-CoV-2 in a virus transport medium for 14 days under different temperatures. The results showed that the novel coronavirus was stable at 4 °C, with only ~0.7-log unit reduction of the infectious titer (~6.8 log $TCID_{50}$/mL) on day 14. At 56 °C, inactivation was readily effectuated within 30 min, which was further reduced to 5 min at 70 °C. Hessling et al. (2020) used published data and the Arrhenius models on thermal inactivation to calculate the temperature and duration of coronavirus inactivation. The study estimated that, for a 5 log-reduction, SARS-CoV-2 could be inactivated within 32.5 min at 60 °C under standard conditions. Abraham et al. (2020) provided estimates on thermal destruction of coronaviruses by lowering viral concentrations to near or below the detectable limit. Based on existing data on exposure temperatures and durations for inactivating coronavirus strains, the study estimated the minimum duration to be 20 min at 50–55 °C, 5 min at 55–60 °C, or 3 min above 65 °C for achieving near-complete destruction of coronaviruses, with 5–7 log reduction and a safety factor recommended for COVID-19.

1.4 Solar heating as a passive strategy for disinfecting COVID-19 in passenger vehicles

Apart from using chemical disinfectants, researchers recently explored alternative methods for disinfecting items potentially contaminated by the novel coronavirus, including ultraviolet irradiation (Zhao et al., 2020), ozonation (Blanchard et al., 2020), and electrical heating (Oh et al., 2020). As Nature's biocide, solar radiation disinfects microorganisms via heat and ultraviolet radiation (Castello et al., 2017). Since ancient times, these benefits have been exploited by humankind for water sanitation and soil disinfection (Gai et al., 2011; Rijal and Fujioka, 2001). During the current pandemic, solar-based disinfection has the potential to be utilized as a convenient passive approach for inactivating SARS-CoV-2 in large enclosed objects with complex interior structures that may be particularly challenging for performing chemical disinfection. While there has been no study to date, we can exploit the thermal sensitivity of SARS-CoV-2 to disinfect the interior spaces of passenger vehicles with suspected COVID-19, by parking them under direct sunlight in a warm or hot weather, *e.g.,* during summer or in areas with "all-year-round" high temperatures (*e.g.*, tropical countries and regions). In this study, we provide the proof-of-concept on this approach by monitoring the time and spatial profiles of temperatures in a typical four-door passenger vehicle left in an outdoor parking lot under direct sunlight on a warm autumn day, with doors and windows closed.

2. Experimental

The experimental vehicle was a white-colored, four-door, compact-size sedan (Volkswagen Lavida, 2013 model) with transparent windshield, rear and side windows, and no sunroof (**Fig. 1**). For this study, the vehicle was parked under direct sunlight in a vacant parking lot on university campus on a warm autumn day (18 September 2020), with its doors and windows closed and the front facing west. Weather was sunny with mostly a clear sky throughout the two-hour experiment between 13:40–15:40, with a gentle breeze (4 m s^{-1}) from the east. Mercury-in-glass thermometers were hung at four different positions to monitor the time and spatial changes of air temperatures inside the cabin. The four points were located in the front and back seat in a diagonal arrangement to measure air temperatures at both the breathing and knee heights of an average seated adult (170 cm). The experimental vehicle was driven a short distance (~ 1 km) out from a garage to the designated lot and parked in shade to avoid direct sunlight prior to the beginning of temperature measurements. Temperatures were read manually from each of the thermometers with data recorded every 5 min.

Temperatures immediately outside the vehicle were recorded concurrently by reading from a thermometer hung in proximity to the body of the experimental vehicle. Local weather data (Beilin district, Xi'an municipality, Shaanxi, China) provided by AccuWeather were recorded as references on outside air temperature.

3. Results and discussion

Temperature measurements in the experimental vehicle are shown in **Fig. 2**. After parking under direct sunlight for 90 min, the air temperature reached 51–56 °C at the four points in the cabin, with the highest temperature recorded in the driver's seat at breathing height and the lowest in the back seat at knee height. Temperature increased rapidly (0.5 ± 0.1 °C min^{-1}) during the first 30–40 min, followed by a phase of slower increase in the next 50–60 min. A plateau was observed in all of the four points monitored inside the vehicle after 90 min, after which a nearly constant temperature difference (~20 °C) was maintained between the outside temperature and air temperatures inside the cabin. Stratification was found in the vehicle interior where the air was maximally 5 °C hotter by moving closer to the front and the upper zone. Oró et al. (2016) found a similar upward temperature gradient in a passenger vehicle exposed under sunlight, where higher air temperatures were measured in the upper zones as well as the horizontal spaces closer to the front of the vehicle. The reason for such a spatial pattern of air temperatures inside the cabin is that both the roof and the windshield of the vehicle received ample direct sunlight irradiation, which also penetrated through the windshield and directly heated up the plastic boards in the front. Although not measured in this study, many of the frequently touched surfaces are likely to register higher temperatures than those measured in the cabin air. Hou (2017) reported that, under direct sunlight, the front instrument panel showed the most rapid increase of temperature inside the vehicle, reaching 56 °C after 18 min and 70 °C after 1 h, at an ambient air temperature of 32–33 °C. Recent studies showed that under these elevated temperatures, the novel coronavirus would be disinfected within several minutes to half an hour (Abraham et al. 2020; Chin et al. 2020; Hessling et al. 2020), making this a viable strategy to passively disinfect COVID-19 in passenger vehicles during warm and hot weather as well as in countries and regions with a tropical climate.

It is important to note that several factors may affect the results of these measurements. For instance, weather conditions would be one of the determining factors of in-vehicle temperatures. Grundstein et al. (2009) showed that, on clear days, the highest cabin temperature averaged at 61 °C in spring and 68 °C in summer, while lower cabin temperatures were generally registered in cloudy days, averaging at 50 °C and 58 °C in spring and summer, respectively. Also, dark-colored vehicles are likely to register higher interior temperatures and faster temperature increases under the same environmental conditions. Dadour et al. (2011) measured the inside temperature of two passenger vehicles of an identical model with different colors. The study found that, on a hot summer day, temperatures inside the cabin of the black-colored vehicle were generally 5 °C higher than those measured in the white-colored vehicle. Apart from these, the size of interior space, availability of sunroof on top of the vehicle, and sealing of airflows are expected to be additional influencing factors on the temporal and spatial distribution of temperatures in vehicles under solar irradiation. Specifically, compact and subcompact-size passenger vehicles have larger surface-to-volume ratios, which are likely to have more rapid increases of temperature inside their cabins under direct sunlight. Likewise, vehicles with sunroofs and tight sealings (*e.g.*, for good acoustics) are subject to more rapid temperature increases and higher cabin temperatures under the same conditions.

In the Northern Hemisphere, many people have experienced a hot summer with heat waves while living in the midst of the COVID-19 pandemic. According to the U.S. National Oceanic and Atmospheric Administration (NOAA, 2020), the January–July 2020 global land and ocean surface temperatures recorded was the second highest in the 141-year record held since 1880, with record high temperatures witnessed in many countries and regions this year. **Table 1** lists the average air temperatures recorded at several locations across the Northern Hemisphere, where both high temperatures and significant numbers of newly confirmed cases of COVID-19 were reported in August and September 2020. While the intensifying temperature extremes indicate climate changes and other wider issues, we can potentially make use of the warmer weather as a practical means of disinfecting COVID-19 in large, enclosed, and movable objects such as automobiles, aircrafts, cruise ships, and shipping containers, using solar heating as a passive and chemical-free approach.

4. Conclusion

The air heated inside vehicles via solar irradiation could be an efficient disinfecting agent for heat-sensitive pathogens, including SARS-CoV-2, in enclosed passenger vehicles. In-vehicle temperatures (52–57 °C) that could disinfect the novel coronavirus within a short time (20–30 min) was readily achieved by parking a white compact-size sedan under direct sunlight for 90 min with doors and windows closed, on a warm autumn day. Where practical, we advocate solar heating as a passive and chemical-free alternative to current recommendation of chemical disinfectants for disinfecting COVID-19 in passenger vehicles, especially those used for shared transportation services such as taxis, rideshares, and other driver-for-hire vehicles. Hot air can infiltrate into areas that are difficult to access by manual cleaning and disinfecting. Compared with the latter, heat disinfection also offers a “cleaner” approach, leaving no hazardous residues on disinfected surfaces or chemical wastes discharged into surrounding environments. In the current pandemic, we also recommend that buyers of used vehicles to expose their newly acquired vehicles under direct sunlight for more than two hours during hot or warm weather, with the doors and windows closed, to mitigate the risks of COVID-19 transmission via vehicle-related routes. As a safety precaution, heat-sensitive objects should be removed from the vehicle to avoid damages or safety hazards before the solar-heating process. After completing the procedure, it is also advisable to ventilate the hot air to avoid exposure to volatile organic chemicals that may be released from the vehicle interior due to the elevated temperatures maintained inside the vehicle throughout the thermal disinfection process.

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Conflict of interest

The authors declare that they have no conflict of interest in this work.

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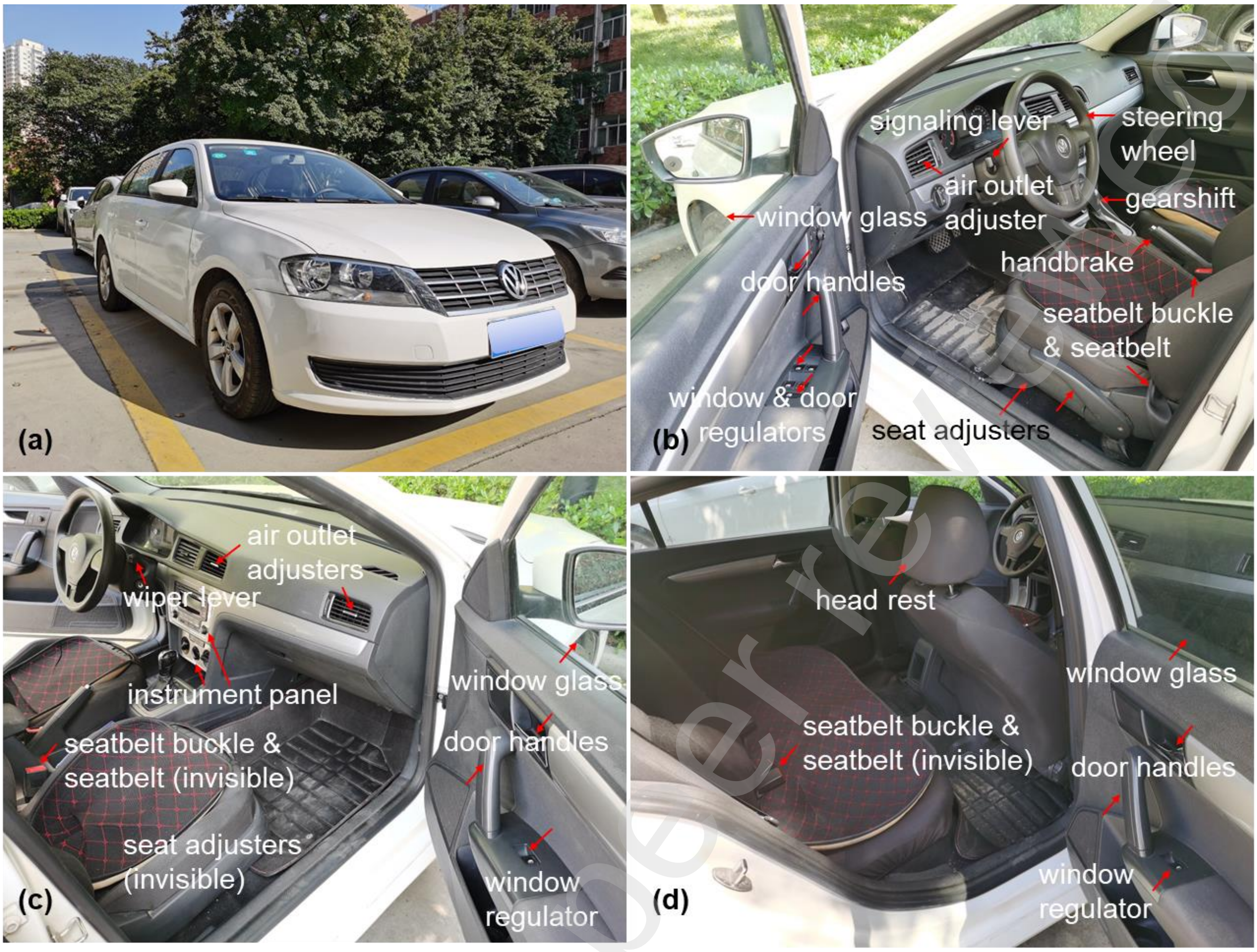

Fig. 1 The experimental vehicle parked in an outdoor parking lot on the university campus with all doors and windows closed and the front of the vehicle facing west. **(a)** The experimental vehicle was a white-colored, compact-size sedan (Volkswagen Lavida, 2013 model), with transparent windshield, rear and side windows, with no sunroof on top. **(b)-(d)** Frequently touched surfaces by driver and passengers in the front and back seat.

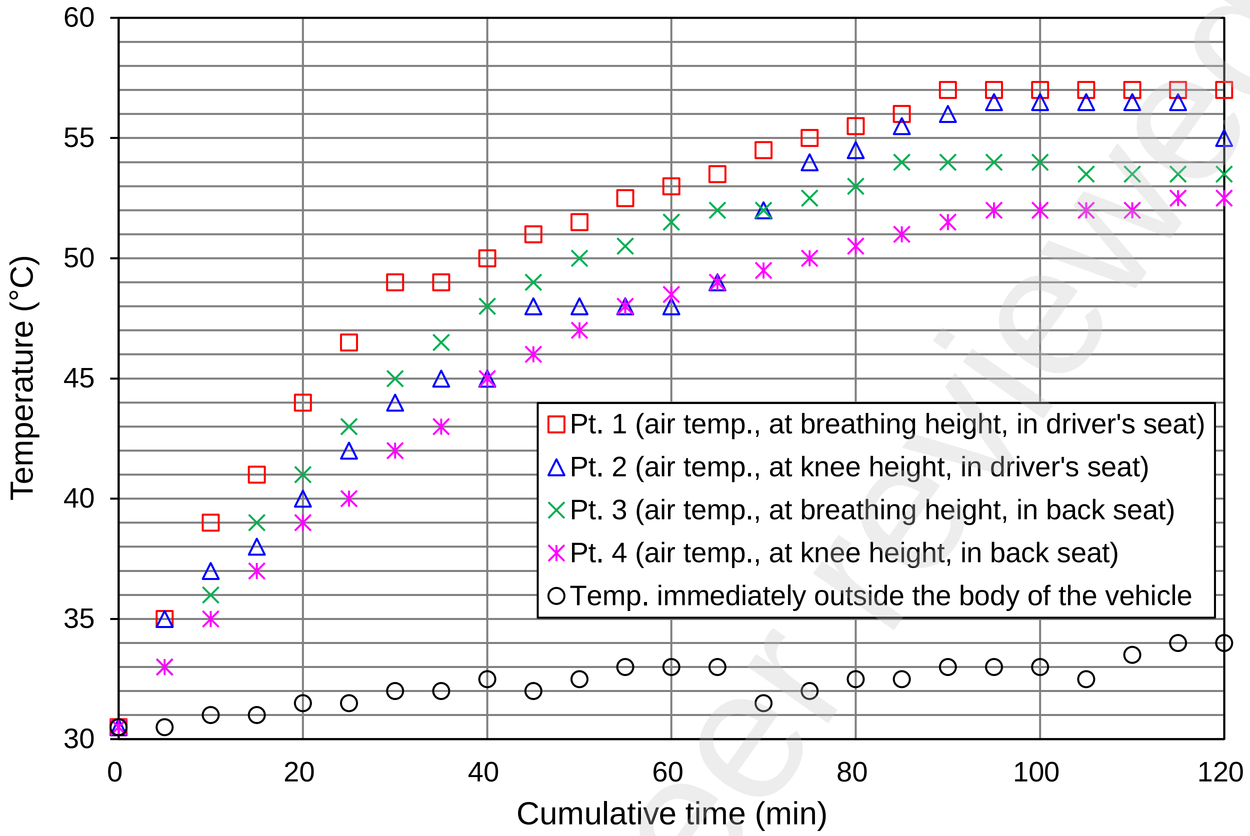

Fig. 2 Air temperature measured in the experimental vehicle during the two-hour experiment. The experiment was performed on a warm autumn day (September 18, 2020) between 13:40 and 15:40, with mostly a clear sky and a gentle breeze from the east (4 m s^{-1}). Mercury-in-glass thermometers were mounted diagonally inside the vehicle to monitor air temperatures in the cabin at the breathing and knee height of an average seated adult (170 cm). Temperatures were read from the thermometers and recorded manually every 5 min. Outside air temperature was 28.0 ± 1.0 °C during our experiment and the temperature immediately outside the body of the vehicle was measured to be 30.5 °C–34.0 °C. Differences were caused by diffuse sunlight and heat radiation from the vehicle after being heated by solar heating.

Table 1. Monthly averages of air temperatures in selected locations across the Northern Hemisphere reporting high temperatures and significant numbers of newly confirmed COVID-19 infections during August and September 2020

	August 1–31, 2020				**September 1–30, 2020**			
Location	**High**	**Average**	**Low**	**Newly confirmed COVID-19 cases**	**High**	**Average**	**Low**	**Newly confirmed COVID-19 cases**
Los Angeles, CA, USA	32.7	25.2	19.5	50,900	33.1	24.8	18.2	27.800
Miami-Dade, FL, USA	32.6	29.3	25.7	35,700	31.7	28.4	25.7	11,300
Harris, TX, USA	35.6	29.7	23.9	31,700	31.5	26.3	22.6	35,200
Dallas, TX, USA	36.4	30.8	25.5	21,000	29.2	24.3	19.1	10,100
Mumbai, Maharashtra, India	29.5	27.7	25.7	30,474	31.2	28.5	26.1	58,321
Pune, Maharashtra, India	26.6	24.0	22.4	83,175	29.6	25.1	22.2	114,466
Chennai, Tamil Nadu, India	33.7	29.9	26.8	34,720	32.7	28.8	25.6	30,679

Notes: Temperature data were obtained from WU (https://www.wunderground.com). Statistics on newly confirmed COVID-19 infections were from Johns Hopkins Coronavirus Resource Center (https://coronavirus.jhu.edu/us-map) and COVID19 India (https://www.covid19india.org).