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Study on Dynamic Characteristics and Influencing Factors of In-vehicle Air Quality under Multiple Scenarios

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Abstract: To investigate the dynamic evolution of in-vehicle air quality in both fuel and new energy vehicles under different scenarios, this study selected four types of test vehicles, new/old fuel vehicles and new/old new energy vehicles. Continuous monitoring was conducted for concentrations of key parameters including CO₂, TVOC, HCHO, and PM_{2.5} under various conditions such as stationary vs. driving states, sealed vs. ventilated modes, different numbers of occupants, and multiple external environments. Using statistical methods such as coefficient of variation analysis and linear regression, the dynamic characteristics of each parameter and their key driving factors were systematically analyzed. The results show that the accumulation rate of CO₂ is strongly positively correlated with the number of occupants, with the rate in fuel vehicles being 1.3–1.6 times that in new energy vehicles, and older vehicles generally exhibiting higher accumulation rates than newer ones. The release of TVOC and HCHO is temperature-driven, with TVOC concentration increasing by up to 0.66 mg/m³ and HCHO by up to 0.04 mg/m³ per 1°C rise in temperature. PM_{2.5} concentration is primarily influenced by the external environment, and the filtration efficiency of the vehicle air conditioning system in external circulation

mode decreases with vehicle age. Underground parking garages represent a high-exposure-risk microenvironment, where pollutants exhibit characteristics of "elevated baseline levels and prolonged persistence." Based on the findings, recommendations are proposed, including standardizing real-time CO₂ monitoring and automatic ventilation systems, conducting full life-cycle emission assessments of vehicle interior materials, optimizing ventilation systems in underground parking facilities, and improving ventilation strategies for occupants, all aimed at enhancing in-vehicle air quality and safeguarding the health of vehicle occupants.

Keywords: in-vehicle air quality; Continuous monitoring; Dynamic characteristics; Influencing factors; Multiple scenarios; Control strategies

1. Introduction

In recent years, with the rapid development of China's economy and the improvement of people's living standards, the number of private cars has shown a sustained growth trend. The number of private cars was increase from 6.54 million in 2010 to 348 million in 2023^[1]. As a result, the car has gradually become one of the most important means of daily transport for people.^[2] The car is the indoor space where people spend the most time every day, apart from their homes and offices. According to surveys, foreigners spend over 1 hour a day in the car, or 5.5% of their total day, while the average Chinese car trip is about 71 minutes, or 4.9% of their total day.^{[2][3]} Vehicle interiors are closed, compact, equipped with materials and equipment, with limited or reduced ventilation and densely occupied compared to indoor spaces. These features make air quality prone to contamination, making the vehicle an important micro-environment for exposure to indoor air pollution.^[4] Pollutant levels in cars are often higher than in residential, office, or hospital spaces.^[5] In addition, the concentration of hazardous compounds in vehicles is 5 to 10 times higher than in homes or offices^[6]. In the 20th century, the United States identified car pollution as one of the top five threats to human health^{[7][8]}.

Poor air quality inside a vehicle can affect the concentration and reaction speed of drivers and passengers.^[9] Some harmful gases may cause symptoms such as dizziness and drowsiness.^[10] For example, a high concentration of CO₂ in a confined space can cause dizziness, headaches, ringing in the ears, vertigo and increased blood pressure.^{[11][12][13]} Standards for Indoor Air Quality^[14] clearly stipulates that the indoor CO₂ concentration should be controlled below 900 ppm. Generally, when the CO₂

concentration reaches 1500 - 2000 ppm, people generally experience shortness of breath, headaches, and dizziness. When it exceeds 2000 ppm, thinking ability is significantly reduced.^{[13][15]} Meanwhile, long-term exposure to low-concentrations of VOCs or formaldehyde in a vehicle can cause headaches, dizziness, hair loss, sensory disturbances, reduced immunity, drowsiness, memory loss, and other adverse reactions.^{[16][17]} For example, at a formaldehyde concentration of 0.06 - 1.2 mg·m⁻³, the nose can detect the odor, and it has an irritating effect on the eyes and respiratory tract.^{[18][19]} At a concentration of 0.06 - 0.07 mg·m⁻³, children may experience mild asthma. When the concentration is around 5 mg·m⁻³, a 30-minute exposure will cause tearing and throat discomfort.^{[20][21]} CO is usually produced by insufficient combustion of fuels, and inhalation is extremely harmful to the human body.^{[22][23]} When the concentration of CO in the air reaches 200 ppm, healthy adults will experience headaches and fatigue after 2 - 3 hours.^{[24][25]}

The direct impact of in-vehicle air quality on passenger health has motivated extensive research. Studies have established that key factors influencing cabin pollutant levels include enclosure time, ambient temperature, and external environmental conditions.^[26] For instance, Zhang *et al.*^[27] demonstrated a positive correlation between vehicular enclosure duration and VOC concentrations, noting a 25% increase in formaldehyde after 32 hours of closure. Complementing this, Liu *et al.*^[28] highlighted the temperature-dependent nature of VOC emissions, with formaldehyde showing particular sensitivity to thermal increases. Research by Hu Houjun^[29] further quantified in-vehicle pollution levels under various real-world driving and ventilation scenarios, reporting significant spikes in CO, NO_x, and VOC concentrations during urban driving, especially in heavy traffic with windows closed. Concurrently, the vehicle cabin is recognized as a dynamic interface with the external environment. Studies confirm that traffic-related pollutants infiltrate the cabin, with in-vehicle concentrations of PM_{2.5}, black carbon, and NO₂ often multiplying ambient levels by factors of 2-3, 4.5, and 1.4, respectively, influenced by air exchange, internal sources, and journey parameters^{[30][31][32]}.

The global transition toward electric vehicles (EVs) has ushered in a new research paradigm. While EVs eliminate tailpipe emissions entirely, they adopt distinct cabin thermal management systems and alternative interior material formulations, making systematic comparisons with traditional fuel vehicles (FVs) not only essential but also vastly underexplored to date^[33]. Moreover, a comprehensive,

quantitative characterization of real-time CO₂ accumulation kinetics across variable occupancy levels and cabin sealing configurations, and the data critical to the design of intelligent ventilation systems, but remains notably lacking. Finally, the impact of specific microenvironments (e.g., enclosed underground parking garages) on acute in-vehicle pollutant exposure peaks has yet to be fully quantified through an integrated analytical framework. To address these critical knowledge gaps, this study designed a controlled multifactorial experiment with following objectives: (1) to quantify and contrast the dynamic accumulation profiles of key pollutants (CO₂, TVOC, HCHO, PM_{2.5}, CO) in FVs and EVs (encompassing both EVs < 3 months old and aged vehicles > 3 years old) under standardized test conditions; (2) to elucidate the mechanistic relationships between cabin thermal conditions, passenger occupancy rates, and secondary pollutant formation; (3) to assess the differential contributions of external microenvironments (open-air parking vs. underground parking, and urban driving scenarios) to in-vehicle pollutant exposure. The findings of this study are intended to provide empirical evidence for the development of tailored cabin ventilation strategies, to inform sustainable material selection for next-generation vehicles, and to support the formulation of public health guidelines aimed at mitigating commuter exposure to in-vehicle air pollutants.

2. Materials and Methods

2.1 Investigated vehicles

In this study, both fuel vehicles (FVs) and electric vehicles (EVs) were included in the experiment, with each category encompassing new models purchased within 3 months and aged models in service for over 3 years. Detailed specifications of the selected vehicles are presented in Table 1.

Table 1 Statistics of experimental vehicles

Information	Fuel vehicles (FVs)		Electric vehicles (EVs)	
New or Old	New	Old	New	Old
Type of gasoline	Gasoline 92	Gasoline 95	/	/
In-vehicle filters	High Performance Filter	High Performance Filter	High Performance Filter	General performance filter
Air purification system	Equipped	Equipped	Equipped	Equipped
Mileage Accumulation	644km	20000km	523km	55000km

2.2 Experimental parameters

The test parameters of this experiment include HCHO, TVOC, PM_{2.5}, CO₂, CO, temperature and humidity. The test points for the cabin air quality were one point in the front air outlet of the cabin (1A), two points in the rear of the cabin for horizontal and vertical (2B and 2C) and one point in the external air inlet of the header (3D), as shown in Figure 1. The air quality inside the car was allowed to stabilize for 10 min at the beginning of the experiment, followed by 20 minutes of continuous sampling and testing using rapid analysis. One set of ambient air data outside the car was tested each day in the morning and afternoon.

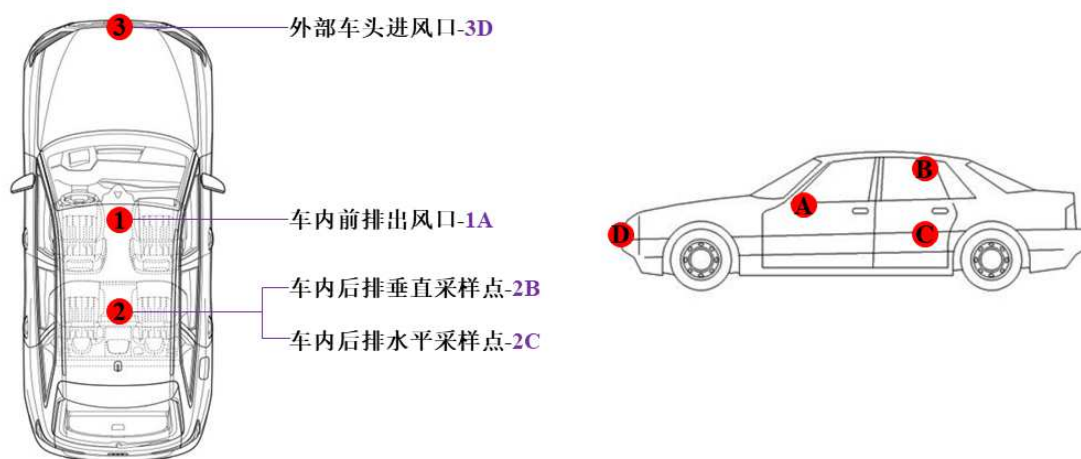


Fig. 1 Points setup of the test vehicles

To investigate the impact of different locations on in-vehicle air quality, the experiment was conducted at three sites. The first site was an open-air parking lot surrounded by buildings on three sides with a single access gate, an independent area separated from external streets and free from interference by passing vehicles. The second site was an underground parking lot with ample parking spaces, which facilitated convenient equipment setup. The third site was a general street with two-way traffic and a wide road surface. The specific layout is shown in Figure 2.



Fig. 2 Actual view of the experimental site

a: Open-air parking lot b: Underground parking lot c: General street

The experimental matrix incorporated five critical vehicular state parameters with defined operational configurations. a) Driving status: stopped, driving. b) Air conditioning status: turned off, air conditioning turned on and set to 24°C. c) Window status: closed, fully open. d) Ventilation status: no ventilation, air recirculation mode (Internal Loop), fresh air intake mode (External Loop). e) number of passengers: 1 person, 5 people. Based on the above vehicle information, vehicle status and site information, different experimental groups were set up and experiments were conducted to investigate the impacts of various experimental conditions on in-vehicle air quality. Experimental group and relevant information are shown in Table 2.

Table 2 Experimental group and relevant information

No.	fuel type	New or Old	driving conditions	Experimental sites	air conditioning status	window states	ventilation status	number of passengers
1#	FVs	New (<3mo)	stop	open-air parking	turned off	closed	no ventilation	1 person
2#					turned off	closed	no ventilation	5 people
3#					turned on (24°C)	closed	internal loop	1 person
4#					turned on (24°C)	closed	external loop	5 people
5#				underground parking	turned off	closed	no ventilation	1 person
6#					turned off	closed	no ventilation	5 people
7#					turned on (24°C)	closed	internal loop	1 person
8#					turned on (24°C)	closed	external loop	5 people
9#			driving	General street	turned off	closed	no ventilation	1 person
10#					turned off	closed	no ventilation	5 people
11#					turned on (24°C)	closed	internal loop	1 person
12#					turned on (24°C)	closed	external loop	5 people
13#					turned off	opened	maximum ventilation	1 person
14#					turned off	opened	maximum ventilation	5 people
15#		Old	stop		turned off	closed	no ventilation	1 person

No.	fuel type	New or Old	driving conditions	Experimental sites	air conditioning status	window states	ventilation status	number of passengers
16#		(>3yr)		open-air parking	turned off	closed	no ventilation	5 people
17#					turned on (24°C)	closed	internal loop	1 person
18#					turned on (24°C)	closed	external loop	5 people
19#				underground parking	turned off	closed	no ventilation	1 person
20#					turned off	closed	no ventilation	5 people
21#					turned on (24°C)	closed	internal loop	1 person
22#					turned on (24°C)	closed	external loop	5 people
23#			driving	General street	turned off	closed	no ventilation	1 person
24#					turned off	closed	no ventilation	5 people
25#					turned on (24°C)	closed	internal loop	1 person
26#					turned on (24°C)	closed	external loop	5 people
27#					turned off	opened	maximum ventilation	1 person
28#					turned off	opened	maximum ventilation	5 people
29#	EVs	New (<3mo)	stop	open-air parking	turned off	closed	no ventilation	1 person
30#					turned off	closed	no ventilation	5 people
31#					turned on (24°C)	closed	internal loop	1 person
32#					turned on (24°C)	closed	external loop	5 people
33#				underground parking	turned off	closed	no ventilation	1 person
34#					turned off	closed	no ventilation	5 people
35#					turned on (24°C)	closed	internal loop	1 person
36#					turned on (24°C)	closed	external loop	5 people
37#			driving	General street	turned off	closed	no ventilation	1 person
38#					turned off	closed	no ventilation	5 people
39#					turned on (24°C)	closed	internal loop	1 person

No.	fuel type	New or Old	driving conditions	Experimental sites	air conditioning status	window states	ventilation status	number of passengers
40#					turned on (24°C)	closed	external loop	5 people
41#					turned off	opened	maximum ventilation	1 person
42#					turned off	opened	maximum ventilation	5 people
43#		Old (>3yr)	stop	open-air parking	turned off	closed	no ventilation	1 person
44#					turned off	closed	no ventilation	5 people
45#					turned on (24°C)	closed	internal loop	1 person
46#					turned on (24°C)	closed	external loop	5 people
47#				underground parking	turned off	closed	no ventilation	1 person
48#					turned off	closed	no ventilation	5 people
49#					turned on (24°C)	closed	internal loop	1 person
50#					turned on (24°C)	closed	external loop	5 people
51#				General street	turned off	closed	no ventilation	1 person
52#					turned off	closed	no ventilation	5 people
53#					turned on (24°C)	closed	internal loop	1 person
54#					turned on (24°C)	closed	external loop	5 people
55#					turned off	opened	maximum ventilation	1 person
56#					turned off	opened	maximum ventilation	5 people

2.3 Test equipment parameters

In this experiment, portable equipment was used to conduct tests for various parameters. The models and specifications of the testing equipment are shown in Tables 3 and 4.

Table 3 Equipment models and parameters

Parameters	TVOC	CO	CO ₂	HCHO
Detection Principle	Photo-ionization PID	electrochemical	NDIR (non-dispersive infrared)	electrochemical
Measurement range	0~20ppm	0~50ppm	0~5000ppm	0~10ppm
Resolution (of a photo)	0.001ppm	0.001ppm	1ppm	0.01ppm
Response time	<30S	<30S	<30S	<30S
Sampling accuracy	±2%FS	±2%FS	±2%FS	±2%FS
Repeatable	±1%FS	±1%FS	±1%FS	±1%FS
Long term drift	≤1% FS/year	≤1% FS/year	≤1% FS/year	≤1% FS/year
Operating temperature	-20~70°C	-20~70°C	-20~70°C	-20~70°C
Preheating time	30S	30S	30S	30S
Storage temperature	-40~70°C	-40~70°C	/	-40~70°C
Working Air Pressure	86~106kpa	86~106kpa	/	86~106kpa

Table 4 Particulate matter equipment parameters

Parameters	PM _{2.5}
Measuring principle	light scatter
Particle Measurement Range	0.3~1.0; 1.0~2.5; 2.5~10
Particle Counting Efficiency	50%@0.3 micron 98%@≥0.5 micron
Effective range of particulate matter mass concentration	0~500 ug·m ⁻³
Maximum range of particulate matter mass concentration	>1000 ug·m ⁻³
Particle mass concentration resolution	1 ug·m ⁻³
Particulate matter mass concentration consistency (PM _{2.5})	±10% @ 100~500 ug·m ⁻³ ±10%@0~100 ug·m ⁻³
Weighing volume	0.1

3. Results

3.1. Assessment of Spatial Uniformity of Pollutant Concentrations inside Vehicles

To scientifically assess the spatial uniformity of pollutant distribution inside vehicles and validate the rationality of using single-point monitoring or multi-point averaging to characterize overall in-vehicle air quality, this study analyzed multiple sets of experimental data collected from four test vehicles (including new/old fuel vehicles and new/old new energy vehicles) under two core states: stationary and driving. The Coefficient of Variation (CV) for each parameter was calculated across three test points (A, B, and C) inside the cabin. As a core statistical measure of data dispersion, the CV offers the advantage of enabling cross-sample comparison of variability while remaining unaffected by data units; a higher value indicates stronger data dispersion, and vice versa. The specific calculation formula is as follows.

$$CV = \frac{SD}{Mean} \times 100\%$$

CV stands for coefficient of variation; SD stands for standard deviation; and Mean stands for mean of multiple data sets.

As illustrated in Figure 3, the Coefficient of Variation (CV) values for temperature, humidity, and pollutants (HCHO, TVOC, CO₂, CO, and PM_{2.5}) were generally less than 5% across the four experimental vehicles under different conditions. This result indicates that, under the experimental conditions defined in this study, the differences between test values at various locations inside the vehicle were minimal, demonstrating a good spatial uniformity of the aforementioned parameters within the cabin. Therefore, the arithmetic mean values of the three sampling points were adopted to represent the overall in-vehicle air quality for all subsequent data analyses. This approach not only simplifies the data presentation process but also ensures the representativeness and reliability of the analysis results.

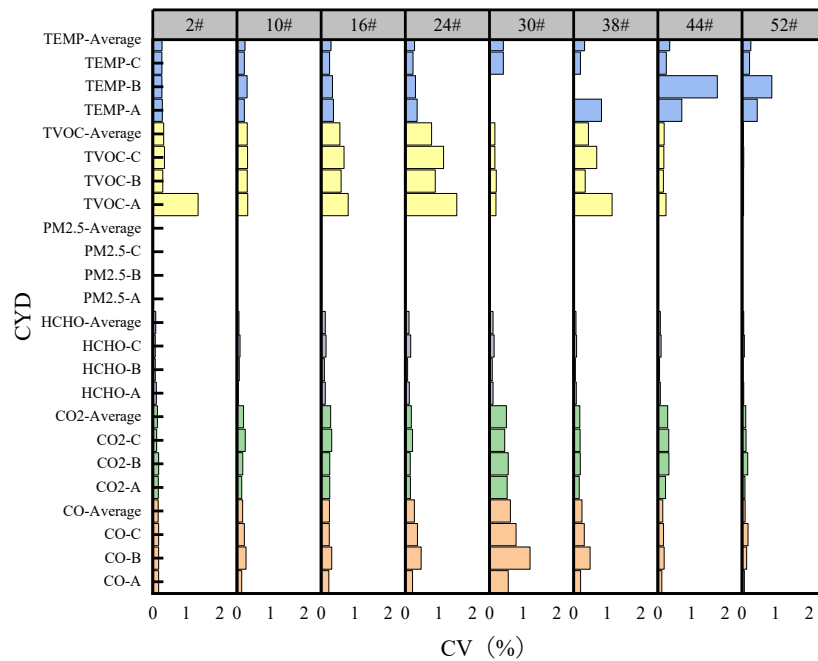


Fig. 3 Coefficient of variation of parameter test values at different points inside the vehicle

3.2. Analysis of Dynamic Changes in Key Parameter Concentrations and Their Influencing Factors

3.2.1 Dynamic Changes in CO₂ Concentration Accumulation

The number of occupants is the core factor driving CO₂ concentration accumulation. Regardless of vehicle type—Fuel Vehicle (FV) or New Energy Vehicle (EV)—the CO₂ accumulation rate in the 5-occupant scenario was significantly higher than in the 1-occupant scenario. As illustrated in Figure 4, taking the New Fuel Vehicle (FV-N) as an example, under closed conditions in an underground parking lot, the average CO₂ accumulation rate for 1 occupant was 1.4 ppm/s, reaching 5732 ppm after 30 minutes, which far exceeds the 5000ppm threshold for severe hypoxia. In contrast, under the 5-occupant scenario, the accumulation rate surged to 7.0 ppm/s, reaching a concentration as high as 16609 ppm after 30 minutes, which is 2.9 times that of the 1-occupant scenario. Even when driving on ordinary streets with windows closed, the CO₂ accumulation rate with 5 occupants (5.6 ppm/s) remained significantly higher than with 1 occupant (0.2 ppm/s), with concentrations reaching 12982 ppm and 1347 ppm after 30 minutes, respectively. CO₂ produced by occupant metabolism is the direct source of elevated

concentrations inside the vehicle, and gas production is positively correlated with the number of occupants.

Vehicle type has a significant and regular impact on the CO₂ accumulation rate. Under the same closed conditions and with the same number of occupants, the CO₂ accumulation rate of FVs was higher than that of EVs, and the rate for older vehicles was generally higher than that for new vehicles. As compared in Figure 5, under the high-risk scenario of "underground parking lot, 5 occupants, fully closed," the average CO₂ accumulation rates for the New Fuel Vehicle (FV-N) and Old Fuel Vehicle (FV-O) were 5.7 ± 0.3 ppm/s and 8.9 ± 0.4 ppm/s, respectively. These rates are significantly higher than those of the New Electric Vehicle (EV-N, 4.3 ± 0.2 ppm/s) and Old Electric Vehicle (EV-O, 5.5 ± 0.3 ppm/s); the average CO₂ accumulation rate for FVs was approximately 1.3 to 1.6 times that of EVs. Based on health threshold calculations, FVs required only 6–7 minutes for CO₂ concentrations to exceed the 5000ppm threshold, whereas EVs required 15–20 minutes. This difference provides a critical basis for formulating ventilation strategies for the two vehicle types. Further analysis suggests that the difference in CO₂ accumulation rates may stem from engineering design disparities between EVs and FVs. First, regarding cabin sealing design: to improve driving range, EVs typically adopt stricter body sealing standards, which reduce air infiltration and exchange between the cabin and the outside environment. Paradoxically, this delays the relative CO₂ accumulation rate under closed conditions. Second, regarding HVAC operational characteristics: during idle tests, the air conditioning compressor in FVs is driven by the engine, which may cause slight fluctuations in engine speed and load, disrupting cabin air pressure balance and indirectly increasing air exchange efficiency, thereby accelerating CO₂ accumulation. Conversely, the HVAC system in EVs is powered directly by the battery, resulting in more stable operation, less disturbance to cabin air pressure, and more stable air exchange. Linear regression verified a strong positive correlation between CO₂ accumulation rate and the number of occupants under closed conditions, with an overall $R^2 > 0.9$. The R^2 and slope under the 5-occupant condition were greater than those under the 1-occupant condition. Furthermore, under the same closed conditions and number of occupants, the regression slope for FV-N was greater than that for EV-N, and the slope for FV-O was greater than that for EV-O. This indicates that in-vehicle CO₂ concentrations are sensitive to changes in the number of occupants, and this sensitivity is higher for FVs than for EVs.

When the vehicle is moving with windows open, the in-vehicle CO₂ concentration can drop rapidly to the ambient background level of 500–600 ppm and remain stable (Figure 4), demonstrating that natural ventilation is the most direct and effective means of eliminating CO₂ accumulation. Even when driving on ordinary streets with windows closed, airflow disturbance around the vehicle body creates a slight negative pressure, enabling a small amount of air exchange. This results in a CO₂ accumulation rate significantly lower than in the stationary closed scenario. For instance, the accumulation rate for a new fuel vehicle with 1 occupant driving on a street with windows closed was 0.17 ppm/s, which is only 1/8 of that in the closed underground parking lot scenario.

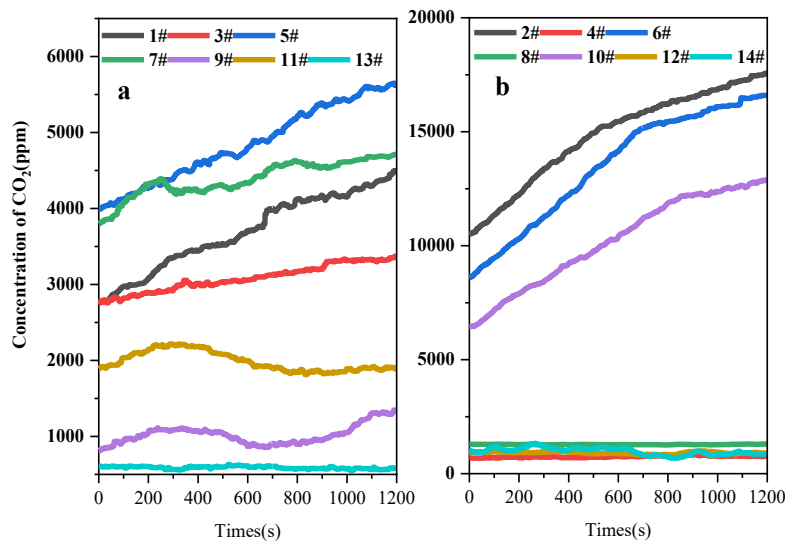


Figure 4. CO₂ concentrations inside new gasoline vehicles under different experimental groups with 1 occupant and 5 occupants.
((a) CO₂ concentrations under different conditions with 1 occupant; (b) CO₂ concentrations under different conditions with 5 occupants.)

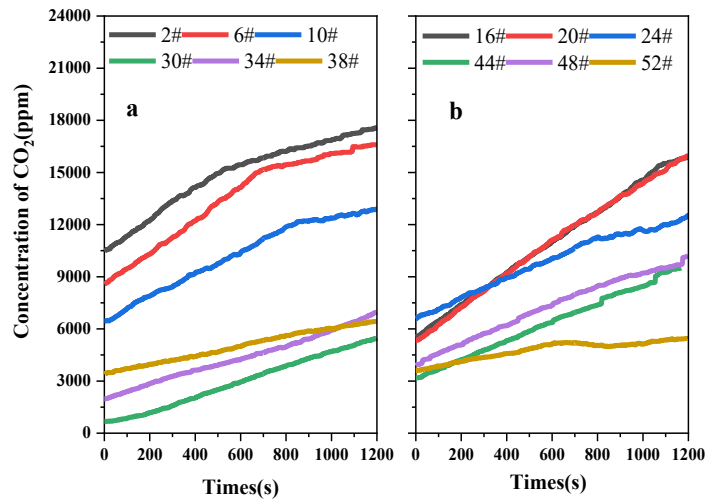


Figure 5. Comparison of in-vehicle CO₂ concentrations under various experimental conditions for different fuel vehicle types.

((a) Comparison of CO₂ concentrations between new gasoline vehicles and new NEVs under closed conditions; (b) Comparison of CO₂ concentrations between old gasoline vehicles and old NEVs under closed conditions.)

3.1.2 Temperature-Driven Emission of TVOC and HCHO

Unlike the influencing factors of CO₂ concentration, the variations in TVOC and HCHO concentrations are primarily driven by temperature, with their peak concentrations occurring under the "windows closed, A/C recirculation" mode. For instance, as shown in Figure 6, the TVOC increase rate in new gasoline vehicles ranges from 0.001 to 0.002 mg/m³·s, reaching a peak concentration of 4.89 mg/m³ after 30 minutes. The HCHO increase rate can reach a maximum of 0.0002 mg/m³·s, with a peak concentration of up to 0.57 mg/m³. In this mode, the combined effect of the thermal load from the A/C system and the metabolic heat production of the occupants causes the in-vehicle temperature to rise gradually (typically by approximately 3°C from the initial temperature), thereby significantly promoting the desorption and emission of TVOC and HCHO from interior materials. Correlation analysis indicates that the steady-state concentrations of TVOC and HCHO are significantly positively correlated with the average in-vehicle temperature. For every 1°C increase in temperature, the TVOC concentration can rise by up to 0.66 mg/m³, and the HCHO concentration by up to 0.04 mg/m³.

The interaction between vehicle type and vehicle age has a significant impact on the emission of TVOC and HCHO. Within the same temperature range, the TVOC concentration in new fuel vehicles is higher than that in new NEVs. For example, in the underground parking lot recirculation scenario

(Experiment Group 3#), the TVOC concentration in new fuel vehicles reached 4.89 mg/m³ after 30 minutes, whereas under the same conditions (Experiment Group 31#), the peak concentration in new NEVs was only 0.32 mg/m³, representing a 15-fold difference. Beyond the emission characteristics of the interior materials themselves, this difference may be related to the micro-vapor permeation from the fuel delivery system in fuel vehicles, a source of pollution avoided by NEVs due to the absence of fuel-related components. Notably, the peak HCHO emission from old NEVs (EV-O) under high-temperature environments exceeded that of old fuel vehicles (FV-O). Figure 7 shows that in the closed underground parking lot scenario, the HCHO concentration in old NEVs reached a maximum of 0.63 mg/m³ after 30 minutes, compared to 0.57 mg/m³ in old fuel vehicles under the same conditions. This phenomenon may be associated with the aging and degradation characteristics of specific polymer materials (such as polyurethane foam and carbon fiber-reinforced composites) adopted in NEVs for lightweighting. After long-term use, the molecular structural stability of these materials decreases, making them more prone to releasing harmful substances like HCHO when driven by high temperatures. Furthermore, while the HCHO concentration in new fuel vehicles is higher than in new NEVs, this trend reverses in the case of old vehicles, indicating that the impact of vehicle age on HCHO emissions is not unidimensional but rather the result of the combined effects of material type, aging degree, and temperature environment.

Under window ventilation conditions, the in-vehicle TVOC and HCHO concentrations can rapidly drop to near the detection limit of the equipment, re-verifying the critical role of fresh air exchange in controlling pollutants. Based on the limits specified in the Guideline for Air Quality Assessment of Passenger Cars (GB/T 27630-2011) (TVOC ≤ 0.6 mg/m³, HCHO ≤ 0.1 mg/m³), the HCHO concentration in new fuel vehicles under the "parking lot, recirculation" scenario exceeded the limit by 5.0 times, while that in new NEVs exceeded the limit by only 1.5 times. This further highlights the severity of interior pollution in new fuel vehicles and the necessity for ventilation intervention.

The PID sensor employed in this study enables rapid monitoring of total TVOC; however, due to differences in response factors for different VOC species, it cannot distinguish specific pollutant components. Future research should combine Gas Chromatography-Mass Spectrometry (GC-MS) technology for species-level identification to clarify the specific components of TVOC emitted by different vehicle models and materials, thereby enabling a more precise assessment of health risks.

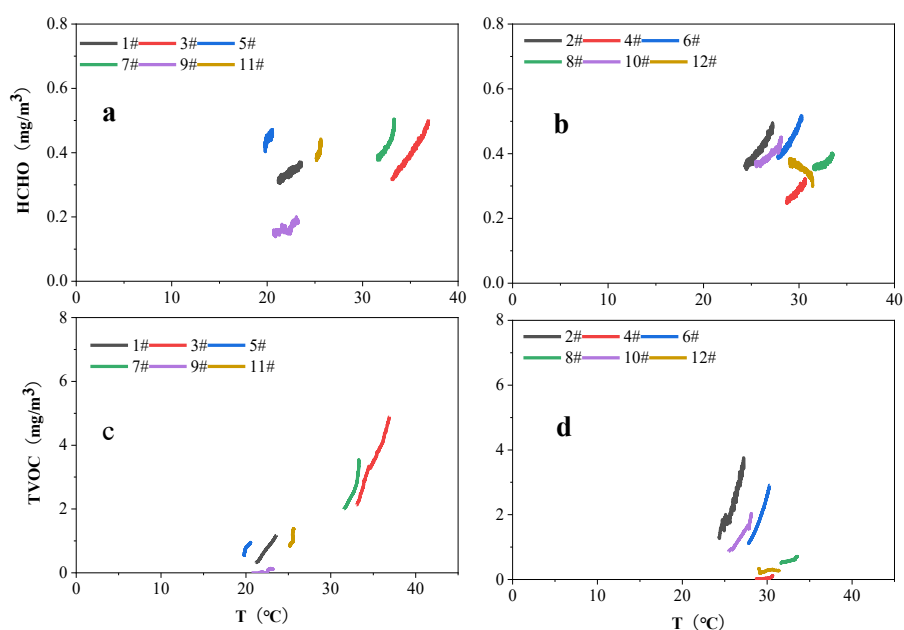


Figure 6. Relationships between in-vehicle HCHO, TVOC concentrations, and temperature in new gasoline vehicles under different experimental conditions.
 ((a) Relationship between HCHO concentration and temperature with 1 occupant; (b) Relationship between HCHO concentration and temperature with 5 occupants; (c) Relationship between TVOC concentration and temperature with 1 occupant; (d) Relationship between TVOC concentration and temperature with 5 occupants.)

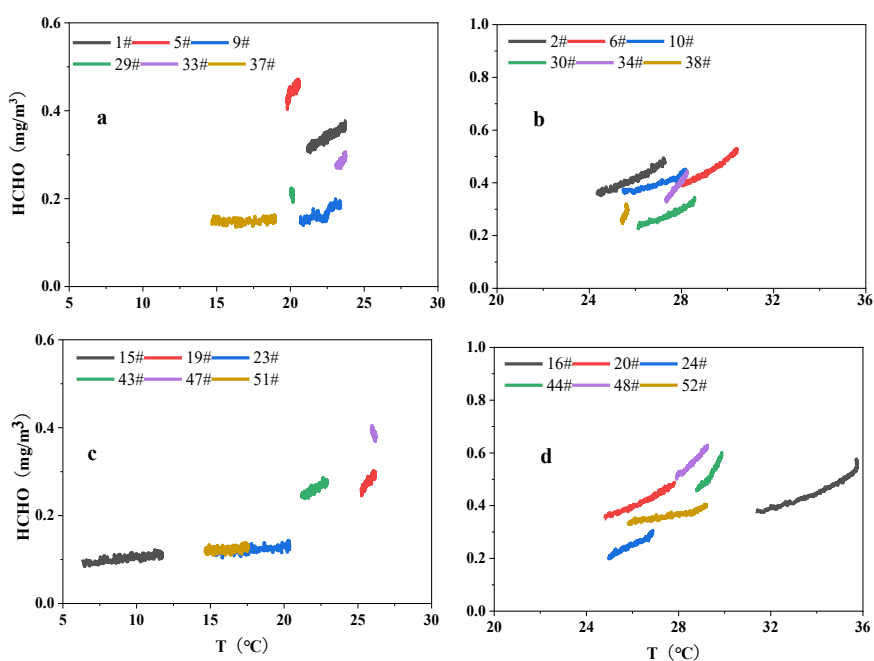


Figure 7. Comparison of in-vehicle air quality under various experimental conditions for different fuel vehicle types.

((a) Comparison of HCHO concentrations between new fuel vehicles and new NEVs with 1 occupant in a closed state at different locations; (b) Comparison of HCHO concentrations between new fuel vehicles and new NEVs with 5 occupants in a closed state at different locations; (c) Comparison of HCHO concentrations between old fuel vehicles and old NEVs with 1 occupant in a closed state at different locations; (d) Comparison of HCHO concentrations between old fuel vehicles and old NEVs with 5 occupants in a closed state at different locations.)

3.1.3 PM_{2.5} Concentration Influenced by External Environment and Air Conditioning Filtration Efficiency

The variation of in-vehicle PM_{2.5} concentration is primarily influenced by external ambient concentrations and air conditioning (A/C) filtration effects, and its dynamic characteristics differ significantly from those of volatile pollutants. In the "window open" or "A/C fresh air (outer circulation)" mode, the in-vehicle PM_{2.5} concentration is highly synchronized with and close to the external ambient concentration, indicating that the external environment is the dominant factor. On test days with good outdoor air quality, the initial in-vehicle PM_{2.5} concentration was generally low; conversely, when outdoor pollution occurred, the initial in-vehicle concentration rapidly climbed to levels close to the interior. The venue environment also had a significant impact on PM_{2.5} concentrations. The outdoor PM_{2.5} concentration in the ordinary street scenario (up to approximately 80 µg/m³) was significantly higher than in open-air parking lots (up to approximately 40 µg/m³) and underground parking lots (up to approximately 40 µg/m³), leading to corresponding increases in in-vehicle concentrations. Furthermore, due to traffic dust and exhaust emissions, outdoor PM_{2.5} concentrations on ordinary streets fluctuated significantly, directly causing synchronous fluctuations in in-vehicle concentrations.

Figure 8 shows that in the natural state without A/C intervention, in-vehicle PM_{2.5} decreases slowly through sedimentation and adsorption by interior materials. When the A/C is activated, the fresh air system demonstrates significant PM_{2.5} filtration effects. As illustrated in Figure 9, which compares in-vehicle and outdoor PM_{2.5} concentrations under A/C fresh air conditions: for new gasoline vehicles, while outdoor PM_{2.5} concentrations fluctuated between 10 and 15 µg/m³, the A/C fresh air system controlled in-vehicle concentrations in test groups 4#, 8#, and 12# to generally below 5 µg/m³, reducing concentrations by over 50% compared to the outside. For new NEVs, when outdoor PM_{2.5} concentrations exhibited distinct peaks (e.g., reaching 30 µg/m³ in group 40#-out), the corresponding in-vehicle PM_{2.5}

concentrations in group 40#-in were significantly suppressed to around $5 \mu\text{g}/\text{m}^3$, effectively blocking high-concentration external pollution. However, for old NEVs facing high outdoor $\text{PM}_{2.5}$ levels (e.g., reaching $80\text{--}120 \mu\text{g}/\text{m}^3$ in group 50#-out), the in-vehicle concentrations in test groups 46#, 50#, and 54#, although lower than outdoor levels, remained at approximately $40 \mu\text{g}/\text{m}^3$. This indicates that automotive A/C filtration efficiency attenuates with increasing vehicle age.

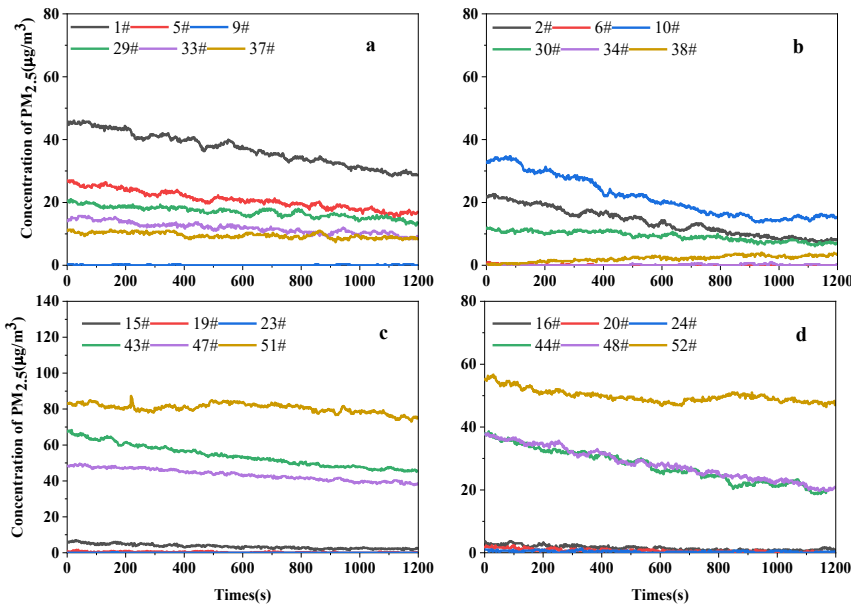


Figure 8. Comparison of in-vehicle air quality under various experimental conditions for different fuel vehicle types.

((a) Comparison of $\text{PM}_{2.5}$ concentrations in new gasoline vehicles and new electric vehicles with 1 occupant in a closed state under different scenarios; (b) Comparison of $\text{PM}_{2.5}$ concentrations in new gasoline vehicles and new electric vehicles with 5 occupants in a closed state under different scenarios; (c) Comparison of $\text{PM}_{2.5}$ concentrations in old gasoline vehicles and old electric vehicles with 1 occupant in a closed state under different scenarios; (d) Comparison of $\text{PM}_{2.5}$ concentrations in old gasoline vehicles and old electric vehicles with 5 occupants in a closed state under different scenarios.)

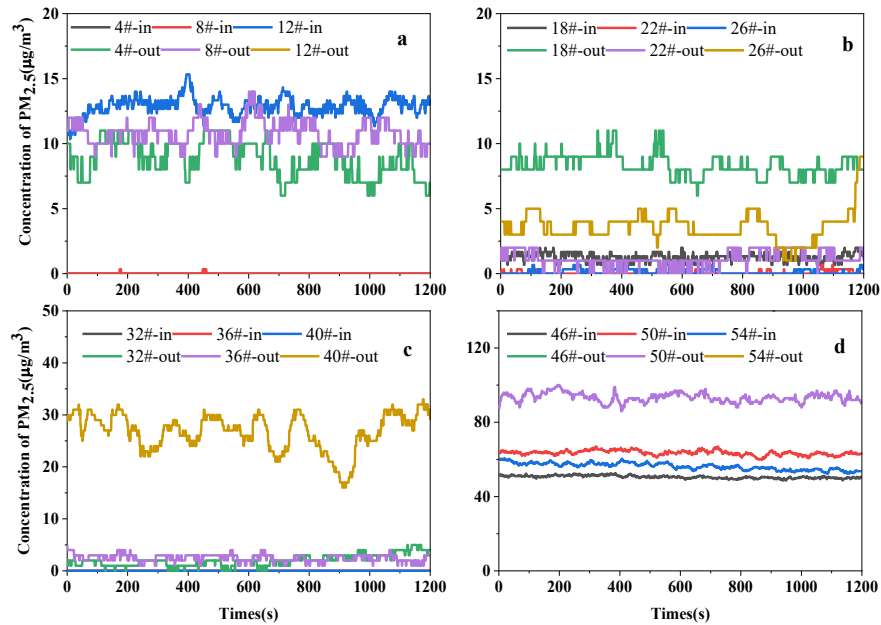


Figure 9. Comparison of indoor and outdoor PM_{2.5} concentrations for various vehicle types under conditions of 5 occupants and A/C fresh air intake.

((a) Comparison of indoor and outdoor PM_{2.5} concentrations in new gasoline vehicles with 5 occupants and A/C fresh air intake; (b) Comparison of indoor and outdoor PM_{2.5} concentrations in old gasoline vehicles with 5 occupants and A/C fresh air intake; (c) Comparison of indoor and outdoor PM_{2.5} concentrations in new electric vehicles with 5 occupants and A/C fresh air intake; (d) Comparison of indoor and outdoor PM_{2.5} concentrations in old electric vehicles with 5 occupants and A/C fresh air intake.)

3.1.4 Comprehensive Impact of Different Site Environments on In-Vehicle Air Quality

By comparing three typical site environments—open-air parking lots, underground parking lots, and ordinary streets—this study found that underground parking lots represent a microenvironment with high exposure risks for in-vehicle air quality, exerting a universal and sustained effect on elevating pollutant concentrations.

Concentrations of characteristic pollutants in underground parking lots were significantly elevated. Even when the experimental vehicles were stationary with engines off, the background CO concentration in the environment was significantly higher than in open-air environments due to poor ventilation and the concentration of vehicle start-stop and idling activities. Consequently, under closed or fresh air (outer

circulation) modes in underground parking lots, the in-vehicle CO concentration was also significantly higher than in the open-air parking lot control scenario. Figure 10 shows that in the scenario with 1 occupant in a closed new fuel vehicle in an underground parking lot (Group 5#), the CO concentration reached 3.5 mg/m³, whereas under the same conditions in an open-air parking lot (Group 1#), it was only 2 mg/m³. Similarly, for a new NEV in a closed underground parking lot scenario with 1 occupant (Group 33#), the CO concentration reached 2 mg/m³, compared to 0.5 mg/m³ in the open-air parking lot (Group 29#).

There are fundamental differences in exposure characteristics between underground parking lots and road driving scenarios. Pollutant exposure during road driving often manifests as brief peaks (e.g., PM_{2.5} and CO peaks influenced by emissions from trucks ahead), typically lasting no more than 5 minutes, and can be rapidly mitigated by closing windows and activating air conditioning recirculation. In contrast, exposure in underground parking lots exhibits characteristics of "high baseline and long duration," where pollutant concentrations remain stably high and rise slowly with prolonged stay, posing potential chronic health risks to drivers and passengers working in this environment for extended periods (such as ride-hailing drivers and underground garage administrators).

Air quality in ordinary street driving scenarios is jointly influenced by traffic flow and ventilation status. In the absence of significant pollution source interference, window ventilation during street driving can maintain low in-vehicle pollutant concentrations. However, during traffic congestion, influenced by exhaust emissions from surrounding vehicles, in-vehicle pollutant concentrations may experience a slight increase. In such cases, closing windows and activating air conditioning recirculation can effectively block external pollution.

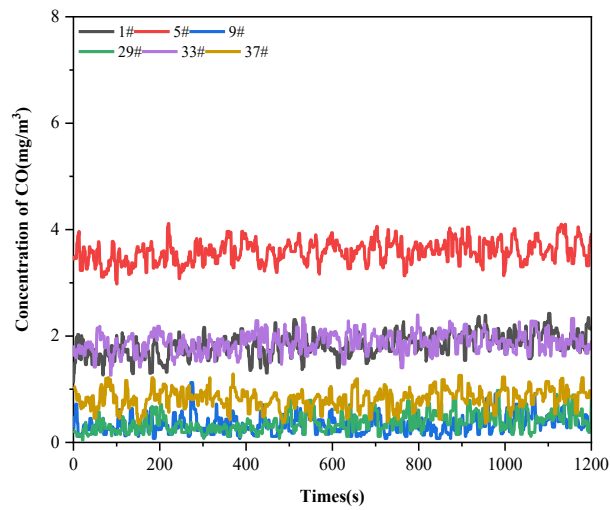


Figure 10. Comparison of CO concentrations in new gasoline vehicles and new NEVs under different scenarios.

4. Conclusions & Recommendations

4.1 Conclusions

Based on systematic comparative experiments across multiple scenarios and vehicle models, combined with statistical analysis and exploration of influence mechanisms, this study elucidated the dynamic evolution patterns and key influencing factors of in-vehicle air quality in both fuel vehicles and new energy vehicles. The main conclusions are as follows:

CO₂ accumulation is identified as a core health risk source. Its accumulation rate is jointly driven by the number of occupants, vehicle type, and vehicle age, with the risk urgency in fuel vehicles being significantly higher than in new energy vehicles. The CO₂ accumulation rate exhibits a strong positive correlation with the number of occupants; the rate in the 5-occupant scenario is significantly higher than in the 1-occupant scenario. Under the same occupancy and closed conditions, the CO₂ accumulation rate in fuel vehicles is 1.3 to 1.6 times that of new energy vehicles, and the rate in older vehicles is generally higher than in new vehicles. In the high-risk scenario of a closed underground parking lot with 5 occupants, fuel vehicles require only 6–7 minutes for CO₂ concentrations to exceed the 5000 ppm severe hypoxia threshold, whereas new energy vehicles require 15–20 minutes, representing a difference in risk onset speed of more than twice. Furthermore, fuel vehicles demonstrate higher sensitivity to changes in occupant numbers, necessitating the formulation of specific ventilation strategies. Window ventilation

can rapidly reduce CO₂ concentrations to ambient background levels (500–600 ppm) and is the most effective risk mitigation measure.

TVOC and HCHO emissions exhibit significant temperature dependence. The interaction between vehicle type and age dominates the differences in pollution levels, and ventilation can effectively manage these risks. For every 1°C increase in temperature, the TVOC concentration can rise by up to 0.66 mg/m³, and the HCHO concentration by up to 0.04 mg/m³. Under the "windows closed, A/C recirculation" mode, concentrations of both pollutants peak due to the increase in in-vehicle temperature (typically by approximately 3°C). Within the same temperature range, the TVOC and HCHO concentrations in new fuel vehicles are significantly higher than in new energy vehicles. However, the peak HCHO release from old new energy vehicles (up to 0.63 mg/m³) surpasses that of old fuel vehicles (up to 0.57 mg/m³), which is speculated to be related to the aging and degradation characteristics of lightweight polymer materials used in new energy vehicles. Window ventilation can rapidly reduce the concentrations of both pollutants to near the detection limit of the equipment, verifying the critical role of fresh air exchange.

The dominant factors influencing in-vehicle PM_{2.5} concentrations are the external environment and A/C filtration efficiency, with the latter exhibiting a certain degree of attenuation as vehicle age increases. In window-open or A/C fresh air modes, in-vehicle PM_{2.5} concentrations are highly synchronized with external levels. Due to traffic dust and exhaust, external concentrations on ordinary streets are significantly higher than in open-air or underground parking lots. The A/C fresh air system demonstrates significant filtration effects; the filtration efficiency for in-vehicle PM_{2.5} concentrations in new fuel vehicles and new energy vehicles is approximately 65%–85%, while the efficiency in older vehicles attenuates to 60%–70%.

Underground parking lots are high-exposure hotspot microenvironments for in-vehicle air quality. The poor ventilation and concentration of pollution sources in these environments lead to significantly elevated concentrations of pollutants such as CO, TVOC, and HCHO inside and outside vehicles. Furthermore, exposure exhibits characteristics of being "high baseline and long duration," which is fundamentally different from the "brief peak" exposure characteristic of road driving scenarios. This poses chronic health risks for personnel with long-term stays, such as ride-hailing drivers and garage administrators.

4.2 Recommendations

It is recommended to promote the standardization of on-board CO₂ real-time monitoring and automatic ventilation systems, and implement differentiated threshold management. Considering the risk differences between fuel vehicles and new energy vehicles, it is suggested that fuel vehicles set a ventilation activation threshold of 2000 ppm for CO₂ concentration, while new energy vehicles set a threshold of 3000 ppm. Additionally, taking into account the impact of vehicle age on CO₂ accumulation rates, the trigger threshold for older vehicles may be appropriately lowered to ensure the timely mitigation of hypoxia risks.

Establish and improve full-life-cycle emission testing standards for new interior materials in electric vehicles. Focus should be placed on the emission characteristics of pollutants, such as HCHO, from lightweight composite materials under long-term thermal aging conditions. Aging emission indicators should be incorporated into the access evaluation system for automotive interior materials to drive the research, development, and application of green interior materials.

Improve the air quality supervision and governance system for underground parking lots. Air quality in underground parking lots should be incorporated into the scope of building environmental health and safety regulations, with clear limit standards defined for pollutants such as CO, TVOC, and PM_{2.5}. Newly constructed underground parking lots should be required to be equipped with high-efficiency ventilation systems and real-time monitoring equipment, and special rectification campaigns should be conducted for existing underground parking lots to reduce exposure risks.

Optimize ventilation and maintenance strategies for drivers and passengers to enhance practicality. During the initial use of new vehicles (especially when stationary in parking lots), window ventilation should be prioritized. For long-term use, vehicle air conditioning filters should be replaced regularly (with a cycle not exceeding 6–12 months; it is recommended to shorten this to 6 months for older vehicles), and high-efficiency filters are recommended for old NEVs. When stopping in underground parking lots or congested traffic sections, windows should be closed and the A/C recirculation mode activated. When driving on ordinary streets with good outdoor air quality, window ventilation should be prioritized to reduce pollutant accumulation.

Focus on the aging emission mechanisms of lightweight materials in new energy vehicles. Future research should utilize Gas Chromatography-Mass Spectrometry (GC-MS) technology for species-level identification of TVOC to compensate for the limitation of PID sensors in distinguishing specific components. Furthermore, the interactive effects of vehicle age, temperature, and material type on pollutant release should be explored to provide data support for more accurate health risk assessments.

Author Contributions

Chenxi Xu: conceptualization, data collection and curation, formal analysis, investigation, methodology, visualization, writing-original draft preparation, review and editing. Yu Bo: methodology, validation, writing-original draft preparation, review and editing, funding acquisition. Chu Wang and WANG Jingming: investigation, methodology, validation, data curation, visualization, writing-original draft. Fubai Li: writing-original draft, visualization. Haiying Li: resources, investigation, methodology. Runcao Zhang, Mengjie Guo, Zimu Jia: data curation, formal analysis, supervision, validation, visualization.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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