Characterizing In-Cabin Environment Using Naturalistic Driving Data in South China

Zhenyu Wang†
Intelligent Transportation Thrust
The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China, 510000
Email: zwang209@connect.hkust-gz.edu.cn

Xiangyu Zhao†
Intelligent Transportation Thrust
The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China, 510000
Email: xzhao432@connect.hkust-gz.edu.cn

Jiahao Zhang
Robotics and Autonomous Systems Thrust
The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China, 510000
Email: jzhang012@connect.hkust-gz.edu.cn

Xu Wen
Intelligent Transportation Thrust
The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China, 510000
Email: s1157942@s.eduhk.hk

Lige Zhao
Department of Civil and Environmental Engineering
The Hong Kong University of Science and Technology, Hong Kong SAR, China, 999077
Email: lzhaobc@connect.ust.hk

Zhe Wang
Department of Civil and Environmental Engineering
The Hong Kong University of Science and Technology, Hong Kong SAR, China, 999077
Email: cezhewang@ust.hk

Dengbo He*
Intelligent Transportation Thrust
The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China, 510000
Email: dengbohe@hkust-gz.edu.cn

Word Count: 4,107 words

Submitted [August 1, 2025]
†Both authors contributed equally to this research. *Corresponding Author

ABSTRACT

The in-cabin environment significantly influences occupant health, comfort, and driving safety, yet its real-world dynamics remain poorly characterized. This study utilized naturalistic driving data from South China to examine the temporal and spatial variability of cabin temperature and CO_2 concentration. A multi-point sensor network—measuring temperature near the foot, torso, and head, as well as CO_2 levels—was deployed in participants' personal vehicles during daily commutes. Analysis of 4484 minutes of data revealed frequent CO_2 exceedances above the 1200 ppm health threshold, with peaks up to 12835 ppm in sedans with three or more occupants. CO_2 levels were already elevated at trip start, suggesting residual accumulation between trips and limited fresh air exchange. Thermal conditions were highly dynamic, particularly during the first 30 minutes, whereas the median trip duration was only 33 minutes—indicating that most passengers experienced unstable thermal conditions. Vertical temperature stratification further highlighted spatial discomfort, with the front row showing more complex and less stable profiles (e.g., V-shaped, descending), while the rear row maintained more uniform distributions. These findings reveal limitations in current HVAC systems, which often fail to respond effectively to occupancy and environmental dynamics. The results underscore the need for intelligent, occupant-aware climate control systems capable of real-time adaptation to ensure a healthy and comfortable cabin environment during real-world driving.

Keywords: Cabin Environment, Thermal Environment, Air Quality

INTRODUCTION

With rapid urbanization and increasing reliance on personal mobility, individuals are spending more time inside vehicles. In the United States, for instance, drivers spend an average of 60 minutes per day behind the wheel [1]. As highly automated driving technologies continue to develop [2], drivers are becoming more likely to perform non-driving tasks in vehicles, such as working or viewing media. This transition is expected to extend travel durations and increase in-cabin occupancy [3], effectively transforming vehicles into a “third space” that parallels homes or offices in daily use.

As vehicle cabins become multifunctional spaces, the quality of the in-cabin environment is emerging as a critical factor for occupant health, comfort, and safety. Two essential aspects of this environment are indoor air quality (IAQ) and thermal comfort [4]. Poor IAQ—particularly the buildup of carbon dioxide (CO_2), a natural byproduct of human respiration—can escalate rapidly in enclosed cabin spaces, especially under high occupancy or low ventilation conditions [5, 6]. Elevated CO_2 concentrations have been linked to impaired cognitive performance, manifesting as drowsiness, reduced vigilance, and delayed reaction times [7, 8]—issues directly relevant to driving safety. Thermal comfort is equally important but particularly difficult to maintain in vehicles due to short trip durations, transient occupancy, variable solar loading, and non-uniform airflow. In the U.S., nearly 60% of vehicle trips are under six miles in length, resulting in usage patterns characterized by frequent entry and exit. These patterns contribute to unstable and transient thermal conditions. Moreover, temperature distribution within the cabin is often spatially heterogeneous, affected by HVAC vent positioning, solar radiation, and occupant body heat—resulting in vertical gradients (e.g., warm head, cool feet) and horizontal gradients (e.g., warmer front row than rear).

Previous research on in-cabin environments has primarily focused on thermal modeling, occupant comfort testing, and HVAC performance optimization [9]. While some empirical studies have examined in-cabin environment conditions, they are typically conducted under controlled laboratory conditions or on-road studies with fixed window states, standardized ventilation settings, and limited occupant activity [5, 6, 10, 11]. Although valuable for assessing system performance, such studies fail to capture the variability and complexity of real-world driving environments.

In real-world scenarios, factors such as fluctuating occupants loads, frequent window openings, diverse vehicle geometries, traffic congestion, and changing weather conditions contribute to highly dynamic and spatially heterogeneous in-cabin environments. Consequently, our current understanding of environmental variation during naturalistic driving remains limited. Bridging this gap is essential for enhancing occupant comfort and informing the development of more adaptive and energy-efficient climate control systems.

This study utilizes naturalistic driving data collected in South China to explore the characteristics of vehicle cabin environments under everyday usage conditions. Specifically, it aims to: (1) quantify typical CO_2 levels and accumulation dynamics during real-world driving, and (2) characterize common temperature distribution patterns (e.g., vertical and horizontal gradients). By addressing these questions, the study seeks to support the design of climate control and environmental monitoring strategies that better adapt to the variability and complexity of actual driving conditions.

METHODS

This study utilizes environmental data collected from a naturalistic driving study conducted in South China (Guangzhou City and its surrounding areas). Data collection from February 2025 to June 2025 and involved participants driving their own vehicles over a period of approximately one to two weeks. The vehicles included commonly models in China equipped with advanced driver-assistance systems, such as Zeekr, XPENG, Xiaomi, Li, and NEO. Each participating vehicle was equipped with three dash cameras to capture driving behavior and traffic conditions. The cameras were installed to monitor 1) the front and rear windshields, 2) the driver’s face and upper body, and 3) the steering wheel, center console, and pedal area. This configuration enabled comprehensive recording of driver behavior, vehicle operation, and external traffic conditions.

To capture in-cabin environmental conditions, temperature and CO_2 sensors were installed at multiple locations within each vehicle, as illustrated in **Figure 1**. Specifically, three temperature sensors (Jaalee JHT-P; accuracy ±0.3 °C) were placed at three vertical positions—foot level, torso level, and head level—at both the driver's seat (front left) and the right rear passenger seat. This setup allowed for assessment of both vertical thermal gradients and spatial differences between front and rear seating areas. In addition, a CO_2 sensor was installed near the driver's head position to monitor in-cabin CO_2 concentration during driving. Depending on availability, two sensor models were used across vehicles: the HOBO MX1102A (accuracy ±50 ppm or ±5%) or the Pengyun S21A2 (accuracy ±50 ppm or ±3%). All sensors recorded data continuously throughout each participant's daily driving routine, allowing the analysis of environmental dynamics under real-world usage conditions. All sensors record data at a frequency of 1 minute and are stored locally on the sensor or uploaded to the cloud.

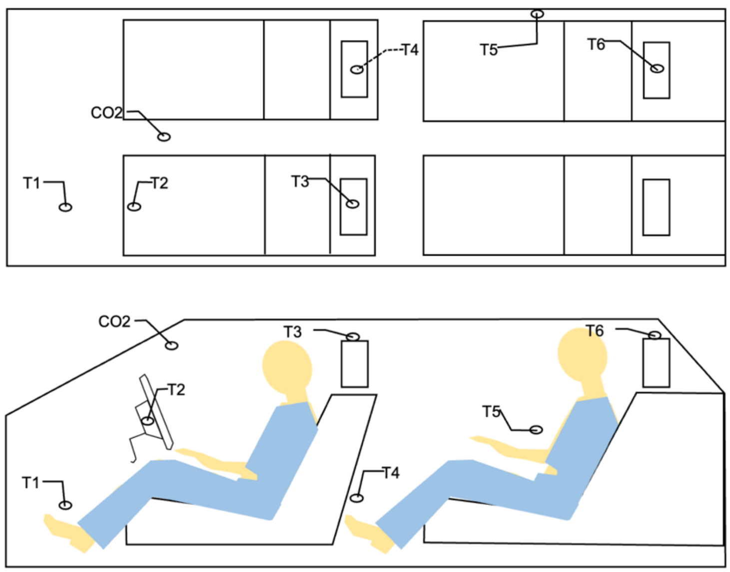

Figure 1 Environmental Sensor Placement

Data Analysis

The analysis began with segmenting the recorded video data to identify the start and end times of each driving trip. A trip was defined as a continuous driving session during which the driver remained inside the vehicle; brief stops (e.g., waiting roadside) and passenger boarding or alighting were permitted. Trip segments were manually annotated from the video footage. Based on the resulting timestamps, environmental data—specifically, temperature and CO_2 concentrations—were temporally aligned. To account for sensor dropouts common in real-world conditions, linear interpolation was applied to missing data segments of up to five consecutive points (equivalent to five minutes). Missing segments exceeding this duration were left as NaN and excluded from subsequent analyses.

Descriptive Analysis

Trips were grouped based on vehicle type and number of occupants. For each group, descriptive statistics were computed for environmental variables, including mean cabin temperature (calculated from the mean of six temperature sensors) and CO_2 concentration.

Dynamic Metrics of Cabin Environment

To quantify temporal variations in the cabin thermal environment, two dynamic metrics were computed using a sliding window (window size: 5 minutes; step size: 1 minute):

- Rate of Change of Temperature (°C/min): This metric captures the speed at which mean cabin temperature changes, providing insight into temperature stability or volatility.
- Temperature Volatility (°C): Defined as the standard deviation of the mean temperature within each window, this metric captures short-term temperature fluctuations, reflecting the degree of thermal instability.

Non-uniformity Metrics of Cabin Temperature

To assess spatial variation in the cabin thermal environment, the following non-uniformity metrics were defined:

- Front–Rear Temperature Gradients: Temperature differences between the front and rear seats were computed at three vertical levels—head (upper), torso (middle), and foot (lower). These gradients reflect horizontal thermal imbalances within the cabin.
- Vertical Temperature Profile Classification: To characterize vertical temperature distribution patterns, each time point was categorized into one of five distinct profile types, based on the relative values of three vertical sensors located at each row (front: T1–T3; rear: T4–T6):
  - Uniform: The maximum vertical temperature difference is less than 3 °C, aligned with the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) 55 standard, which recommends a temperature difference of less than 3 °C between head and ankle levels to avoid thermal discomfort for seated occupants [12].
  - Ascending: Temperature increases with height (Head > Torso > Foot).
  - Descending: Temperature decreases with height (Foot > Torso > Head).
  - V-shaped: The torso is cooler than both the head and the foot.
  - A-shaped: The torso is warmer than both the head and the foot.

RESULTS

Descriptive Analysis

A total of 4484 minutes (74.73 hours) of in-vehicle environmental data were collected. **Table 1** summarizes the environmental conditions across different vehicle types and occupant numbers.

Overall, CO_2 concentrations varied considerably depending on both vehicle type and occupancy level. Specifically, CO_2 levels increased with the number of occupants, and SUVs generally exhibited lower CO_2 concentrations than sedans within the same occupancy category. In all scenarios, the mean CO_2 concentrations significantly exceeded the recommended health threshold of 1200 ppm [13], with the highest instantaneous value reaching 12835 ppm in the "Sedan with 3+ occupants" condition.

With respect to temperature, the mean cabin temperature across all scenarios ranged from 22.92 °C to 27.26 °C. However, extreme instantaneous values were observed, with temperatures dropping as low as 17.38 °C and rising as high as 42.87 °C. These fluctuations likely reflect vehicle startup conditions during cooler seasons and heat buildup due to prolonged sun exposure during summer. Interestingly, the increase in occupant number did not lead to a significant rise in average cabin temperature, suggesting that the air conditioning systems were sufficiently capable of offsetting the additional thermal load from multiple passengers.

TABLE 1 Environmental Data

Vehicle Type	Occupant Number	CO2 Concentration (mean, min-max)	Cabin Temperature (mean, min-max)	Total Duration (min)
SUV	1 Occupant	1463.54, 296-6422	26.04, 19.76-42.87	1014
	2 Occupants	1750.83, 264-6422	22.92, 17.38-37.16	893
	3+ Occupants	2141.76, 335-6021	25.09, 21.8-33.84	233
Sedan	1 Occupant	1763.85, 446-5020	27.36, 23.28-36.39	906
	2 Occupants	2853.99, 447-6972	26.83, 23.33-36.53	687

	3+ Occupants	3922.86, 412-12835	25.98, 22.43-32.98	751

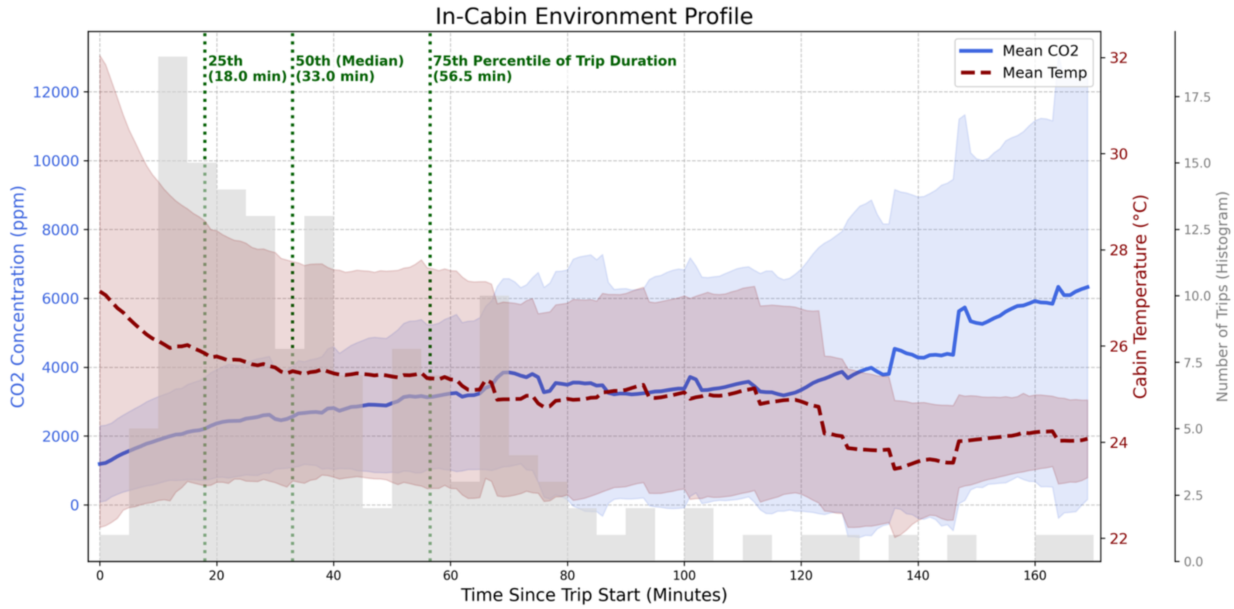

Figure 2 In-Cabin Environment Profile

Figure 2 illustrates the overall trends in in-cabin environmental conditions across all trips, plotted against trip duration. The gray histogram in the background indicates that most trips lasted less than one hour, with a median duration of 33 minutes.

Superimposed on this, the CO_2 concentration (blue curve) shows a continuous increase during the initial phase of the trip, eventually reaching a plateau after approximately one hour. Notably, CO_2 levels were already near the health threshold of 1200 ppm at the beginning of most trips. This suggests that in real-world driving conditions, CO_2 exposure may be more severe than typically assumed, as cabin air quality is influenced by residual buildup from the previous trip and does not necessarily reset to match outdoor air quality.

Simultaneously, the mean cabin temperature (red curve) displays a rapid decrease at the beginning of the trip, followed by a gradual stabilization. However, stabilization often occurs close to the one-hour mark, implying that for the majority of trips, the temperature may not have reached optimal comfort levels before the trip concluded.

Although data from trips exceeding one hour were relatively limited, the available records indicate that CO_2 concentrations can continue to accumulate over time, potentially reaching levels comparable to those observed in enclosed underground environments. Such elevated concentrations may significantly impact occupants' thermal comfort, degrade perceived air quality, and negatively affect emotional state and cognitive performance [14]. Meanwhile, mean cabin temperature during these longer trips continued to exhibit a gradual decline. However, due to the small sample size for extended trips, these trends warrant further investigation in future studies.

Dynamic Metrics of Cabin Environment

To investigate the temporal dynamics of cabin temperature, a sliding window approach was employed to compute the rate of change and volatility of the mean cabin temperature, as illustrated in **Figure 3**.

At the onset of the trip, temperature exhibits a sharp negative rate of change, with an average cooling rate reaching up to –0.1 °C/min. This reflects the initial intensive cooling phase of the air conditioning system. Between 30 and 60 minutes, the rate of change gradually stabilizes around zero, and after 60 minutes, it shows minor fluctuations around this equilibrium. Although longer-duration trips are less represented in the dataset, this fluctuation suggests that the cabin environment remains highly dynamic due to factors such as window opening, ventilation adjustments, and varying solar radiation. A similar pattern is observed for the standard deviation of cabin temperature, where periods of rapid cooling are associated with greater short-term variability in temperature.

Overall, by the end of most trips (i.e., up to the 75th percentile), both the rate of change and volatility of cabin temperature tend to approach a steady state.

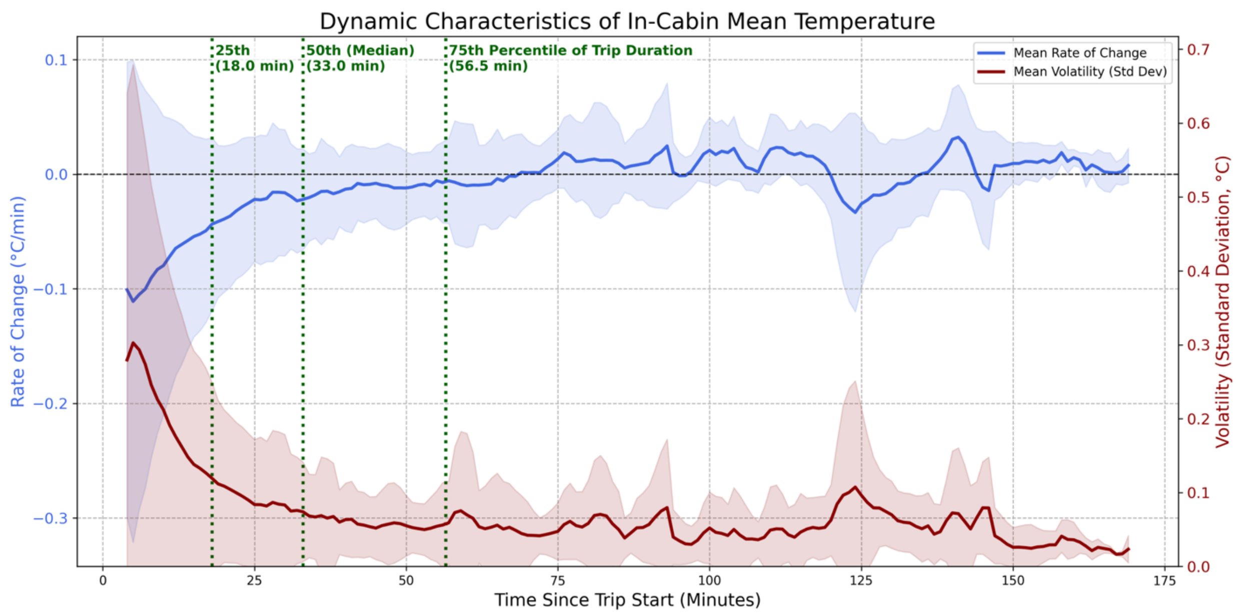

Figure 3 Dynamic Characteristics of In-Cabin Mean Temperature

Non-uniformity of Cabin Environment

Figure 4 illustrates the temporal evolution of temperature differences between the front and rear seats across three vertical levels. The temperature gradients exhibit complex trends. At the head level, the front–rear temperature difference remains consistently around 0 °C throughout the first hour of trips, indicating similar thermal conditions between rows. At the torso level, the front-seat temperature starts lower than the rear but gradually increases, surpassing the rear temperature after approximately 40 minutes. In contrast, the foot level shows a stable pattern, with the front seat consistently about 1 °C warmer than the rear.

Figure 5 illustrates the temporal evolution of vertical thermal stratification patterns for both the front and rear seats. In the front row, three key observations emerge: 1) At the beginning of the trip, nearly 60% of the measurements exhibit a uniform vertical temperature profile. This proportion gradually and intermittently increases over time, reaching nearly 100% after approximately 100 minutes. 2) Among the non-uniform distributions, the most dominant pattern is the V-shape (i.e., torso cooler than both head and foot), followed by the descending profile (temperature decreases with height). These two patterns are consistent with the typical sensation of cold air being directed at the upper body from the front air vents. 3) The ascending (temperature increases with height) and A-shape (torso warmer than both head and foot) profiles were observed too. These patterns may result from more complex thermal interactions, such as low solar elevation angles causing increased solar load on the torso region or the natural sinking of denser cold air, warranting further investigation.

In contrast, the rear row exhibited a simpler and more stable pattern. Over 80% of the measurements at the start of the trip were classified as uniform, with this share fluctuating before eventually reaching 100%

after approximately 110 minutes. Among non-uniform patterns, only the ascending and A-shape profiles were observed.

Overall, the results suggest better airflow uniformity in the rear row compared to the front, which may be attributed to the greater number of air vents and increased solar exposure in the front cabin area—particularly through the windshield—introducing additional thermal disturbances.

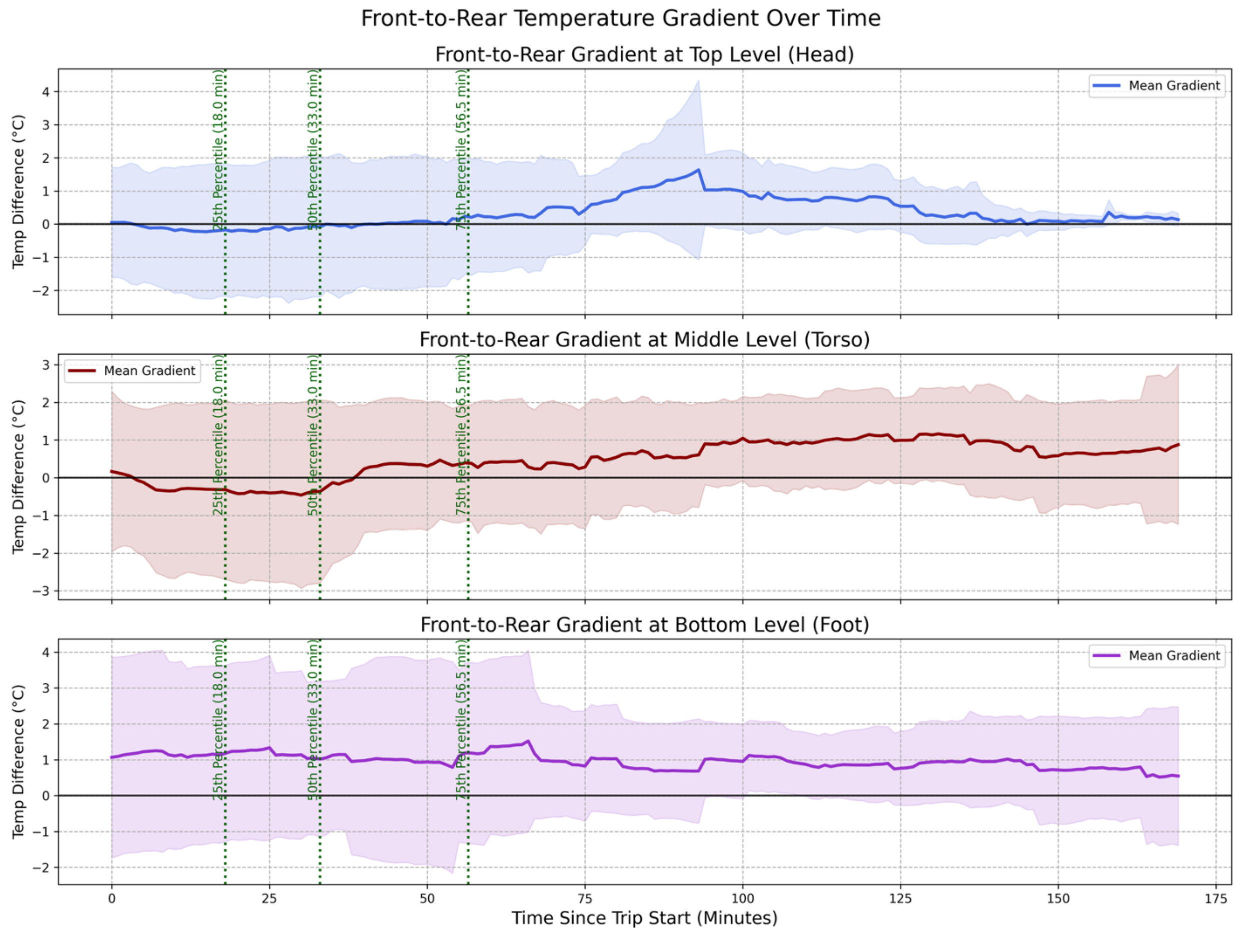

Figure 4 Front-to-Rear Temperature Gradient Over Time

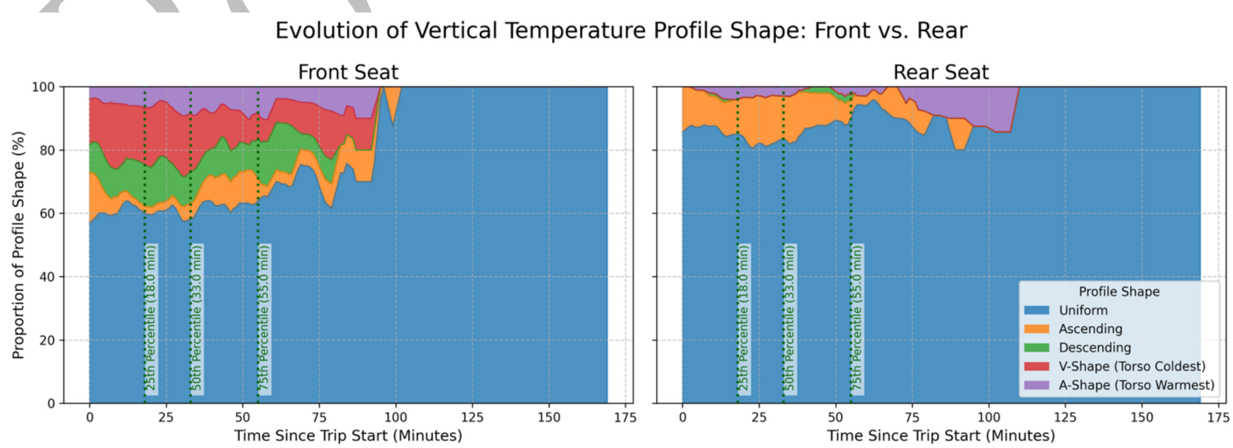

Figure 5 Vertical Temperature Profile Shape Over Time

DISCUSSION

CO_2 Characteristics in Cabins

One key finding of this study is the significant and rapid accumulation of CO_2 within the vehicle cabin. Across all vehicle types and occupancy levels, the average CO_2 concentration exceeded the 1200 ppm threshold recommended by health and safety standards such as ASHRAE. In the worst-case scenario—sedans carrying three or more occupants—the mean CO_2 concentration reached 3922.86 ppm, with peak levels as high as 12835 ppm. Furthermore, elevated CO_2 levels were observed at the beginning of most trips, suggesting that in real-world driving conditions, CO_2 exposure may be more severe than typically assumed. This is likely due to residual accumulation from previous trips, as cabin air quality does not necessarily reset to ambient outdoor conditions before each trip. As trip duration increases, CO_2 continues to accumulate, eventually reaching levels comparable to those found in enclosed underground environments.

These findings underscore the limitations of static or manually controlled ventilation systems, which often fail to respond effectively to dynamic changes in occupancy and air quality. Accordingly, the results support the implementation of occupant-aware, demand-controlled ventilation strategies. These intelligent systems—potentially incorporating real-time CO_2 sensing or camera-based occupant detection—could dynamically adjust the intake of fresh air to maintain a healthy in-cabin environment, thereby enhancing both comfort and safety without requiring active intervention from the driver.

Thermal Characteristics in Cabins

The analysis of temperature variation reveals that the early phase of each trip was characterized by high thermal volatility and a rapid rate of temperature change, reflecting the aggressive initial cooling of HVAC systems. Notably, the median trip duration (33.5 minutes) overlaps with this unstable phase, indicating that, for a considerable portion of typical commutes, occupants are exposed to a constantly shifting rather than thermally stable environment. As a result, not only is the thermal load on the vehicle system increased, but the experience of thermal discomfort may also arise, which can negatively impact cognitive states and driving performance, thereby undermining driving safety.

In addition, the spatial aspect of thermal distribution presents an additional challenge. Our findings show that a single-point temperature reading is insufficient to represent the occupant’s actual thermal experience. The cabin environment exhibits pronounced spatial non-uniformity, particularly in vertical temperature stratification. Specifically, the front row showed more complex and less stable patterns than the rear, with a higher incidence of non-uniform profiles such as V-shaped and descending distributions. This can be attributed to the combined effects of direct HVAC airflow and greater solar exposure through the windshield. In contrast, thermal conditions in the rear row were generally more stable and homogeneous. These spatial differences suggest that thermal disturbances induced by airflow and solar load are more pronounced in the front cabin, leading to uneven thermal sensations among occupants.

These findings underscore the need for more nuanced climate control strategies that account for both temporal dynamics and spatial variations in cabin conditions. In particular, the design of in-cabin climate systems should integrate considerations of airflow distribution and solar radiation dynamics to ensure comfort and safety, especially for front-seat passengers.

Limitations and Future Work

This study, while offering valuable real-world insights, is subject to several limitations. First, we did not have access to the CAN bus data of vehicles, which would have provided critical information about HVAC control parameters such as temperature setpoint, fan speed, and airflow mode. Without this data, it is difficult to assess how driver behavior and system settings influenced the observed environmental conditions. Second, the current analysis is purely descriptive and does not account for potential confounding factors such as seasonality, weather conditions, or vehicle speed, all of which may impact temperature regulation and CO_2 accumulation. In addition, the absence of direct solar radiation measurements limits our ability to quantify its contribution to thermal load and spatial non-uniformity. Future work should include solar irradiance sensors to better capture this influence, particularly given its known impact on front cabin overheating. Integrating these data streams would allow for more accurate modeling of in-cabin microclimates and support the development of adaptive HVAC control systems.

CONCLUSIONS

Leveraging naturalistic driving data from South China, this study characterized in-cabin environmental dynamics using multi-point sensors to capture real-world CO_2 and temperature variations. Our findings reveal that CO_2 concentrations frequently exceeded the recommended 1200 ppm threshold, with levels reaching up to 12835 ppm in sedans with three or more occupants. The thermal environment was highly volatile during the initial phase of trips, meaning occupants experience a constantly shifting, rather than stable, climate for a significant portion of their commute. Furthermore, significant spatial non-uniformity was observed, with complex vertical temperature stratification, such as V-shaped profiles, being more pronounced in the front cabin due to direct airflow and solar load.

Collectively, these results demonstrate that current HVAC systems struggle to maintain a healthy and comfortable micro-environment under the dynamic conditions of everyday driving. This study highlights the urgent need for intelligent, occupant-aware climate control systems that can adaptively respond to real-time changes in both air quality and thermal distribution to enhance driving safety and comfort.

ACKNOWLEDGMENTS

The authors would like to thank ChatGPT of OpenAI for assistance with grammar checking and language refinement during the preparation of this manuscript.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Zhenyu Wang, Xiangyu Zhao, Jiahao Zhang; data collection: Zhenyu Wang, Xiangyu Zhao, Jiahao Zhang, Xu Wen; analysis and interpretation of results: Zhenyu Wang, Xiangyu Zhao, Lige Zhao, Zhe Wang, Dengbo He; drasft manuscript preparation: Zhenyu Wang, Xiangyu Zhao. All authors reviewed the results and approved the final version of the manuscript.

DECLARATION OF CONFLICTING INTERESTS

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FUNDING

This work was supported by the "1+1+1" joint funding scheme from the Guangdong Provincial Department of Science and Technology (GDST), the Hong Kong University of Science and Technology (Guangzhou) (HKUST(GZ)), and the Hong Kong University of Science and Technology (HKUST).

REFERENCES

1. Z. Xi and S. Rebecca, "American Driving Survey: 2023 (Research Brief)," Washington, D.C., 2024. [Online]. Available: https://aaafoundation.org/american-driving-survey-2023/
2. S. Doll. "California certified as next US state to allow Mercedes' Level 3 autonomous DRIVE PILOT." Electrek. https://electrek.co/2023/06/08/california-certified-us-mercedes-level-3-autonomous-drive-pilot-driving/ (accessed.
3. S. Acharya and M. Mekker, "Acceptance and demand of autonomous vehicles for long-distance recreational travel: An investigation based on a survey of visitors to US national parks," Transportation Research Part A: Policy and Practice, vol. 186, 2024, doi: 10.1016/j.tra.2024.104157.
4. M. Frontczak and P. Wargocki, "Literature survey on how different factors influence human comfort in indoor environments," Building and Environment, vol. 46, no. 4, 2011, doi: 10.1016/j.buildenv.2010.10.021.
5. G. Mathur, "Use of Partial Recirculation to Limit Build-Up of Cabin Carbon Dioxide Concentrations to Safe Limits per ASHRAE Standard-62," SAE International, Warrendale, PA, SAE Technical Paper 2020-01-1245, 2020-04-14 2020. Accessed: 2024-10-15 09:27:35.
6. Y. Zhao, C. Jiang, and X. Song, "Seasonal patterns and semi-empirical modeling of in-vehicle exposure to carbon dioxide and airborne particulates in Dalian, China," Atmospheric Environment, vol. 274, p. 118968, 2022-04-01 2022, doi: 10.1016/j.atmosenv.2022.118968.
7. J. Zhang, X. Cao, X. Wang, L. Pang, J. Liang, and L. Zhang, "Physiological responses to elevated carbon dioxide concentration and mental workload during performing MATB tasks," Building and Environment, vol. 195, p. 107752, 2021-05-15 2021, doi: 10.1016/j.buildenv.2021.107752.
8. D. Chen, G. Huebner, E. Bagkeris, M. Ucci, and D. Mumovic, "Effects of short-term exposure to moderate pure carbon dioxide levels on cognitive performance, health symptoms and perceived indoor environment quality," Building and Environment, vol. 245, 2023, doi: 10.1016/j.buildenv.2023.110967.
9. L. Zhao, Q. Zhou, and Z. Wang, "A systematic review on modelling the thermal environment of vehicle cabins," Applied Thermal Engineering, vol. 257, p. 124142, 2024, doi: 10.1016/j.applthermaleng.2024.124142.
10. R. A. Angelova, D. G. Markov, I. Simova, R. Velichkova, and P. Stankov, "Accumulation of metabolic carbon dioxide (CO2) in a vehicle cabin," (in en), IOP Conference Series: Materials Science and Engineering, vol. 664, no. 1, p. 012010, 2019-10 2019, doi: 10.1088/1757-899X/664/1/012010.
11. N. Hudda and S. A. Fruin, "Carbon dioxide accumulation inside vehicles: The effect of ventilation and driving conditions," Science of The Total Environment, vol. 610-611, pp. 1448-1456, 2018-01-01 2018, doi: 10.1016/j.scitotenv.2017.08.105.
12. Thermal Environmental Conditions for Human Occupancy, ASHRAE, 2017 2017.
13. Ventilation for Acceptable Indoor Air Quality, ASHRAE, 2016 2016.
14. Z. Xie et al., "Field Investigations on Subjective Perception, Physiological Responses, and Cognitive Performance under Increasing CO2 Concentration in an Underground Confined Space," (in en), Indoor Air, vol. 2024, no. 1, p. 5781565, 2024 2024, doi: 10.1155/2024/5781565.