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IMPACT OF VENTILATION SETTING ON CARBON DIOXIDE (CO_2) ACCUMULATION IN A COMPACT CAR CABIN ENVIROMENT

Muhammad Zaki Zainal[1*], Norsheila Buyamin[1] and Mohd Saiful Saleh[1]

[1]*Mechanical Engineering Deparment, Politeknik Ungku Omar, Ipoh, Malaysia*

[*]*muhammadzakizainal@gmail.com*

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ABSTRACT

Indoor air quality (IAQ) in vehicle cabins is a growing concern, particularly due to rising carbon dioxide (CO_2) levels in enclosed environments during prolonged occupancy. This study investigates the behavior of CO_2 concentration over time under various ventilation and operational conditions in a compact vehicle cabin. The primary objective is to evaluate the impact of ventilation mode (recirculation vs. fresh air), vehicle status (static vs. running), and time of day (AM vs. PM) on CO_2 accumulation, referencing established standards such as ASHRAE and SAE. A total of eight experimental setups were conducted using a Perodua Axia, involving two to four passengers over 60-minute per sessions. CO_2 and temperature were monitored at ten-minute intervals using the GE Telaire® 7001 CO_2/Temperature Monitor. Key parameters such as fan speed and AC setting were held constant to ensure reliable comparisons. Meanwhile the number of occupants count increases from 2 passenger to 4 passenger by time. Data were analysed by plotting CO_2 concentration versus time to visually and statistically evaluate air quality trends. Results revealed that CO_2 levels increased significantly under static and recirculated air conditions, often surpassing the 1000 ppm threshold within 10–15 minutes, indicating potentially unsafe indoor air quality. In contrast, the use of fresh air ventilation in a running vehicle showed the most effective dilution of CO_2, maintaining levels well within safety guidelines. The study concludes that fresh air mode in a moving vehicle offers the best strategy for minimizing CO_2 buildup and ensuring occupant comfort and safety.

1. Introduction

In recent years, increasing attention has been given to indoor air quality (IAQ), particularly in enclosed spaces such as vehicle cabins. As urban populations continue to rely heavily on personal vehicles for daily commuting, the quality of air inside cars becomes critical for human health and cognitive performance. Among the various pollutants present in enclosed spaces, carbon dioxide (CO_2) is of primary concern due to its strong correlation with ventilation effectiveness and occupant load (Ye et al., 2017). High concentrations of CO_2 in vehicle cabins are typically caused by recirculation mode operation and inadequate air exchange with the outside environment, especially during idle conditions or in traffic jams.

While CO_2 is not inherently toxic at moderate levels, prolonged exposure to concentrations above 1000 ppm has been associated with drowsiness, impaired concentration, and reduced cognitive performance (Bierwirth., 2021). To safeguard occupant health, standards from ASHRAE (2019), OSHA (2021), and SAE J2762 recommend maintaining in-cabin CO_2 levels below 1000–1200 ppm. However, comprehensive field data comparing CO_2 levels across different vehicle conditions such as static vs. moving status, ventilation modes (fresh vs. recirculated air), and varying times of day remain limited. This data gap is critical, given that current automotive HVAC systems are typically optimized for thermal comfort, often prioritizing cooling efficiency by recirculating air, rather than ensuring adequate ventilation.

The mode leverages pressure differentials created by HVAC blower fans to introduce outside air, improving overall ventilation effectiveness (Xin et al., 2024). Hence, for static morning conditions, direct air mode is more favourable for maintaining acceptable air quality. Overall, driving with closed air circulation significantly increases CO_2 buildup, potentially impairing alertness and safety, while direct air intake helps maintain safer CO_2 levels (Persily & de Jonge, 2017). In closed-air recirculation, these conditions accelerate thermal stress, leading to higher metabolic rates in occupants and thus higher CO_2 output (El-Fadel & Abi-Esber, 2009). However, urban afternoon traffic may increase the risk of introducing polluted air, requiring HVAC filters to mitigate PM2.5 or NOx while still reducing CO_2 (Barnes et al., 2018; Chen et al., 2020). Such elevated levels are known to impair cognitive function and induce drowsiness, thereby compromising both driver alertness and passenger health (Satish et al., 2012).

Many vehicle users are unaware that this default operation can lead to rapid CO_2 buildup, especially in stationary traffic or when multiple passengers are present. Without real-time air quality monitoring or adaptive ventilation control, in-cabin air may reach unhealthy levels, potentially compromising driver alertness and safety. Therefore, this study aims to evaluate CO_2 concentration trends in a compact car cabin under real-world conditions, focusing on the effects of ventilation mode, vehicle operating status, and time of day, benchmarked against established indoor air quality standards (Hudda & Fruin, 2018). Therefore, the objective of this study is to evaluate the impact of ventilation mode (recirculation vs. fresh air), vehicle status (static vs. running), and time of day (AM vs. PM) on CO_2 accumulation, referencing established standards by referring to the established standards ASHRAE (<1000 ppm), SAE (<2500 ppm), and OSHA (<5000 ppm) (Liu, 2021). By doing so, the study hopes to provide insight into how specific combinations of ventilation mode (recirculation vs. fresh air), vehicle status (static vs. running), and time of day (AM vs. PM) influence in-cabin CO_2 buildup, with direct implications for minimizing exposure to elevated CO_2 levels that may impair cognitive function, cause discomfort, and pose health risks during daily commutes or prolonged travel. The remainder of this paper is organized as follows: Section 2 outlines the methodology of this study. Section 3 and 4 presents results and discusses the results obtained from analysis, respectively. Finally, Section 5 concludes the paper with key findings and directions for future research.

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2. Methodology

This research investigates carbon dioxide (CO_2) concentration behavior inside the cabin of a compact car (Perodua Axia) under varying operational conditions, specifically comparing static vs. running modes and fresh air (direct air) vs. recirculated air (closed air) ventilation during both morning and evening periods. The study is grounded in a controlled experimental methodology that includes real-time data acquisition and analytical comparisons based on internationally recognized indoor air quality standards. The main variable for this study shown in Table 1.

Table 1. Main variable for this study

Main Variable	**Units and conditions**
Vehicle operating condition	Static or running
Ventilation mode	Recirculated or fresh air
Number of occupants	2 to 4 passengers
Parameters	CO_2 concentration and running time
Device	GE Telaire® 7001 CO2/ Temperature monitor

To ensure consistency, the experimental design incorporated a set of controlled variables, including a fixed route of for running tests, a 60-minute duration for each scenario, a low air conditioning temperature setting, medium fan speed, and a constant driving speed of 60–80 km/h. Boundary conditions were also defined: ambient CO_2 had to be under 600 ppm before each test, all doors and windows were sealed, and the AC system operated continuously in a single mode (fresh or recirculated) without switching. For static tests, the engine remained idling during this period. These conditions simulate typical hot-climate urban commuting and idling scenarios, allowing for accurate evaluation of ventilation performance and in-cabin gas accumulation.

Figure 1. GE Telaire® 7001 CO2/Temperature monitor

The GE Telaire® 7001 CO2/Temperature monitor was chosen for its reliable accuracy and dual-function monitoring of CO_2 and temperature. Using Non-Dispersive Infrared (NDIR) sensing technology, the device provided accurate measurements (±50 ppm or ±5% of reading) within a range of 0–10,000 ppm for CO_2 and 0–50°C for temperature. Data output included a real-time LCD display and analog export functionality. The sensor was installed at the rear seat headrest to approximate the passenger breathing zone and was zero-calibrated in open air before each test. Data were recorded every 10 minutes over a 60-minute period for each of the eight experimental conditions as Table 2. All readings were logged manually and verified with photographs, and the resulting datasets were structured into tables with time, CO_2 concentration, and temperature, which were then used to plot CO_2 trends over time for comparative analysis.

Table 2. Experimental condition

Ventilation mode	Vehicle operating condition	Time
Recirculated (closed air)	Static	AM
Fresh air (direct air)	Static	AM
Recirculated (closed air)	Running	AM
Fresh air (direct air)	Running	AM
Recirculated (closed air)	Static	PM
Fresh air (direct air)	Static	PM
Recirculated (closed air)	Running	PM
Fresh air (direct air)	Running	PM

3. Results

Static Conditions – Close vs. Direct Airflow (AM)

In static morning conditions, the CO_2 level inside a vehicle cabin is heavily influenced by the selected air intake mode. When operating and recirculation mode (closed air), the HVAC system continuously reuses the internal cabin air without introducing fresh external air. This method is designed to improve cooling efficiency by maintaining internal thermal loads (Wei et al., 2023). However, due to continuous human respiration in an enclosed space, CO_2 concentrations increase rapidly as there is no outlet or dilution mechanism for exhaled gases. This leads to CO_2 accumulation that can exceed 1000 ppm within 10–15 minutes in static conditions as Figure 2. The accumulation lies in the closed-loop air cycle, which traps carbon dioxide and other metabolic byproducts. In contrast, using direct air mode (fresh air intake) in Figure 3 allows for external air to replace stale in-cabin air, facilitating constant dilution of CO_2 levels.

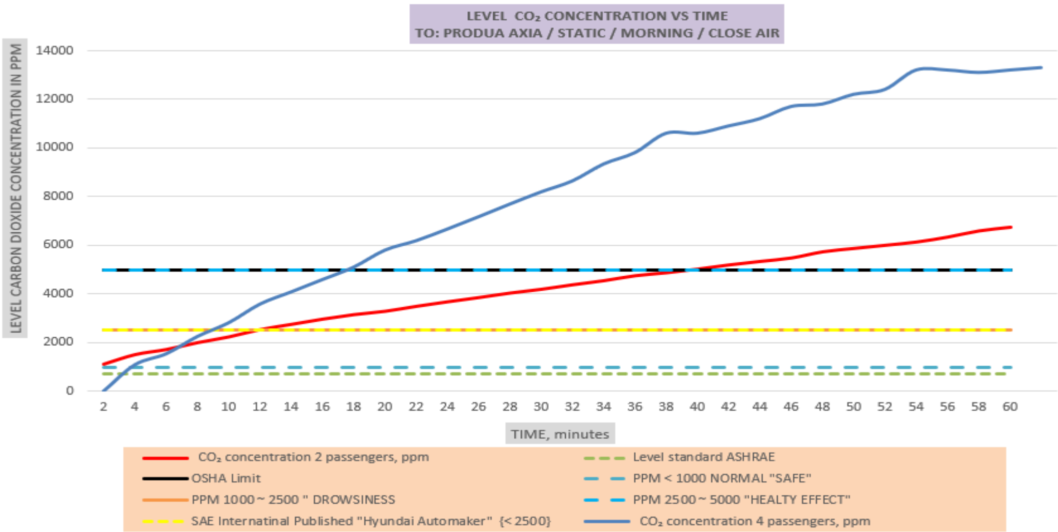

Figure 2. Axia static in close air in AM

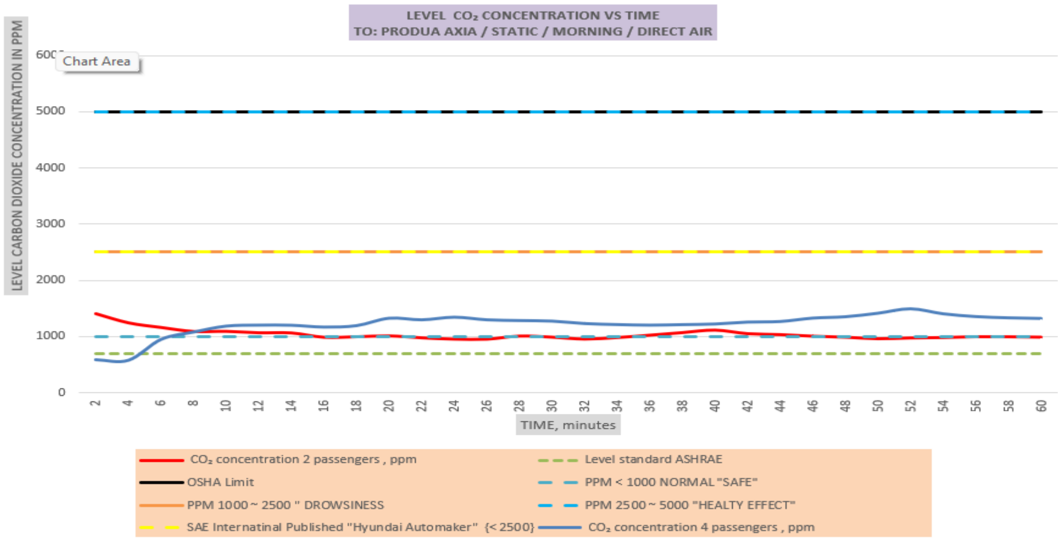

Figure 3. Axia static direct air in AM

3.2 Running Conditions – Close vs. Direct Airflow (AM)

In the closed air condition in Figure 4, CO_2 levels frequently exceed 1000 ppm and often reach or surpass 2000 ppm, even peaking near the SAE International recommended upper limit of 2500 ppm. This range (1000–2500 ppm) is associated with drowsiness and reduced cognitive performance (Satish et al., 2012). At multiple points, levels dip below 1000 ppm but remain mostly elevated, suggesting poor ventilation. In contrast, the direct air condition in Figure 5 keeps CO_2 concentrations largely below 1000 ppm, with only a brief spike above this level. This indicates better air exchange and reduced buildup of exhaled CO_2, aligning with ASHRAE standards for acceptable indoor air quality.

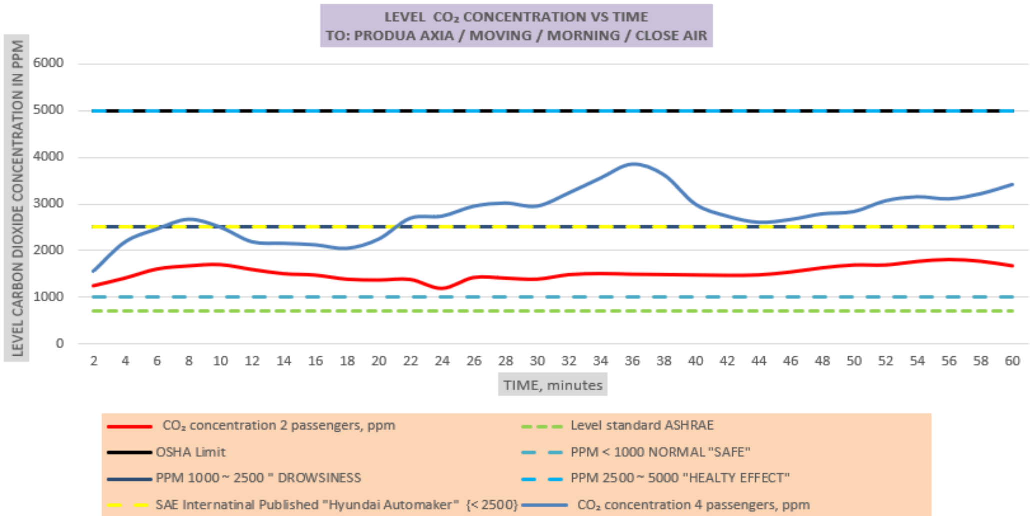

Figure 4. Axia running close air in AM

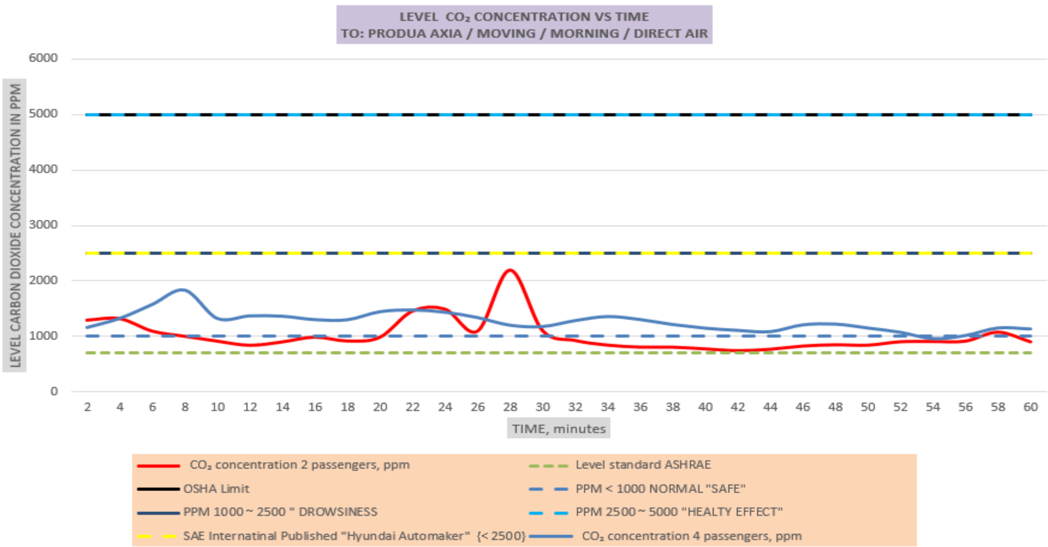

Figure 5. Axia running direct air in AM

3.3 Static Conditions – Close vs. Direct Airflow (PM)

Based on Figure 6 and 7, in the afternoon, static conditions exacerbate CO_2 buildup due to the compounded effect of higher ambient temperatures and extended vehicle exposure to sunlight. In this case the physiological response to heat, where increased breathing rates result in greater CO_2 emissions. Simultaneously, the HVAC system in recirculation mode is overburdened, often prioritizing temperature control over air exchange. This results in inefficient CO_2 displacement. Conversely, in direct air mode, ambient air even if warm is continuously introduced, allowing for natural convection and CO_2 reduction through positive pressure ventilation. By using external airflow to displace contaminated internal air without relying solely on refrigerant cycles. Despite such external pollution risks, direct air mode remains technically superior in lowering CO_2 under static PM conditions.

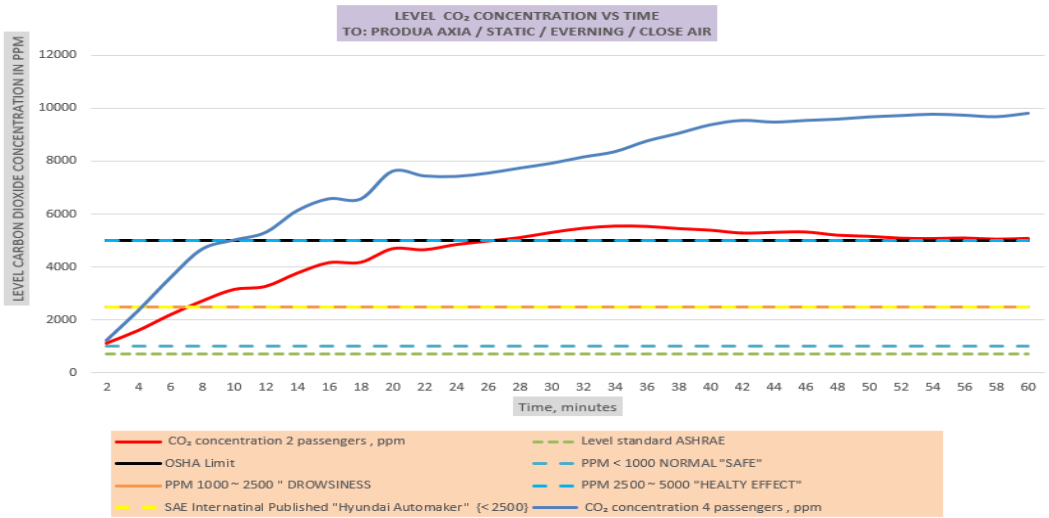

Figure 6. Axia static in close air in PM

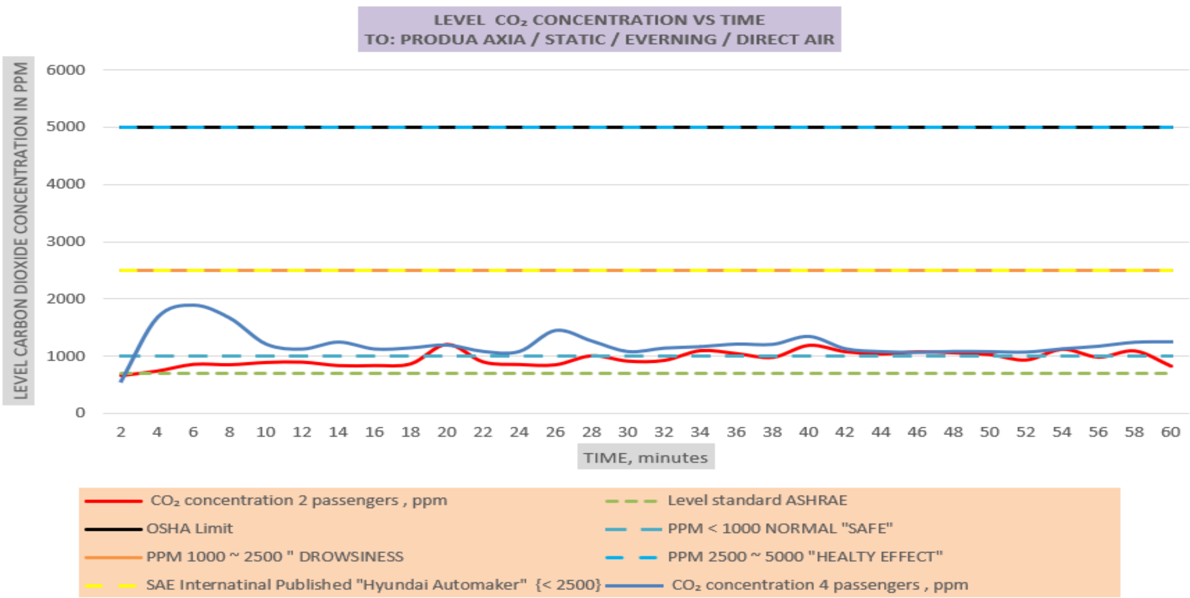

Figure 7. Axia static direct air in PM

3.4 Running Conditions – Close vs. Direct Airflow (PM)

Based on Figure 8 and Figure 9, In the closed-air scenario, CO_2 concentrations rise sharply, frequently exceeding 2500 ppm and peaking over 5000 ppm. These values significantly surpass safety thresholds outlined by ASHRAE (<1000 ppm), SAE (<2500 ppm), and OSHA (<5000 ppm). By contrast, the direct-air scenario keeps CO_2 levels consistently below 1000 ppm, with only brief minor peaks. This demonstrates that allowing external air into the cabin dilutes CO_2 concentrations effectively. Ventilating the cabin either by opening windows or using the vehicle's fresh air intake mode enables continuous air exchange, thus maintaining CO_2 at safe, non-drowsy levels.

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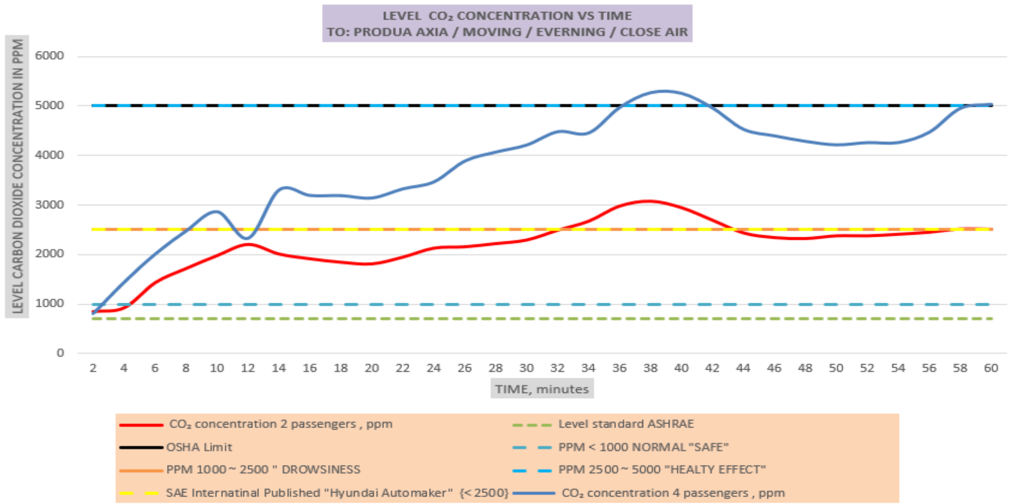

Figure 8. Axia running close air in PM

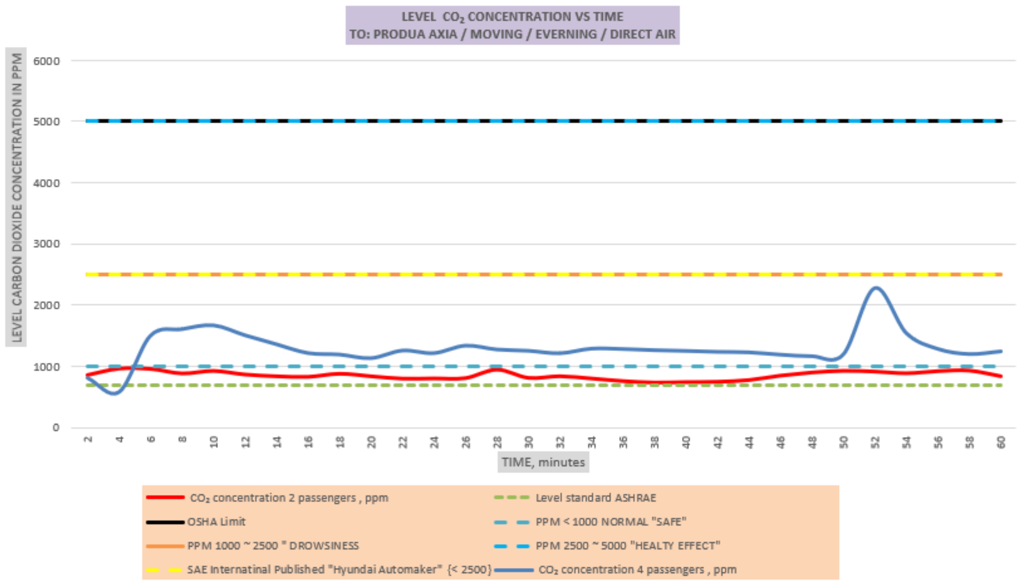

Figure 9. Axia running direct air in PM

4. Discussion

Based on Figure 10 and Figure 11, across both static and dynamic conditions in AM and PM periods, recirculation mode consistently resulted in higher CO_2 accumulation due to its limited or absent air exchange mechanism. The technical disadvantage of this mode lies in its closed-loop operation, which prioritizes temperature efficiency over ventilation. The increase in CO_2 under closed-air conditions occurs due to the lack of ventilation, which causes exhaled air to accumulate. The continuous of human CO_2 emission that overwhelms closed environments without external dilution. In a confined space like a car cabin, human respiration is the primary source of CO_2 buildup, particularly when the air is recirculated and not exchanged with outdoor air (Chang et al., 2024; Elaouzy & El Fadar, 2022). On the other hand, direct air mode, while

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slightly less efficient in maintaining thermal loads, offers substantial benefits in maintaining healthy CO_2 concentrations, particularly in long drives or high-occupancy scenarios. The direct air ventilation involves balancing fan speed, intake duct positioning, and filter resistance to optimize clean airflow into the cabin. This study supports existing literature advocating for intelligent HVAC systems that incorporate CO_2 sensors and adaptive air mode switching to automatically balance comfort, air quality, and energy use(Wei et al., 2023). Elevated CO_2 concentrations are known to impair cognitive performance, reduce alertness, and cause discomfort symptoms that can be particularly dangerous during driving. According to Satish et al. (2012), CO_2 levels as low as 1000–2500 ppm can impair decision-making and concentration, which directly impacts road safety. The extremely high concentrations observed in static, recirculated-air scenarios could therefore pose serious health and safety risks, especially in long idling situations such as traffic jams or waiting periods. From a comfort perspective, high CO_2 levels are often associated with stale air, drowsiness, and headaches, reducing the overall quality of the commuting experience. The significant difference between fresh air and recirculated modes emphasizes the importance of ventilation design in vehicle engineering. Automotive manufacturers should consider default settings that favor periodic fresh air intake, especially under idle conditions. Future vehicle cabin designs must emphasize active air quality management systems that not only maintain acceptable CO_2 levels but also integrate smart energy and pollutant control algorithms for occupant health and safety.

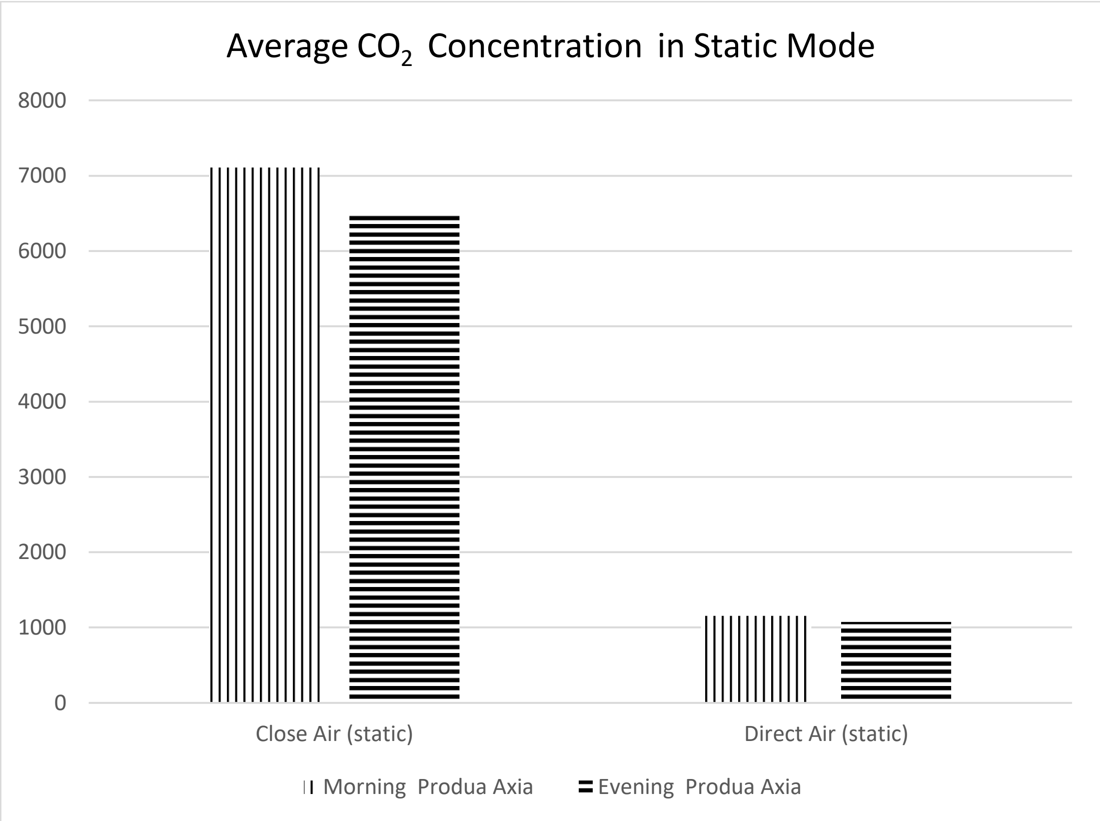

Figure 10. Average CO2 concentration in Static Mode

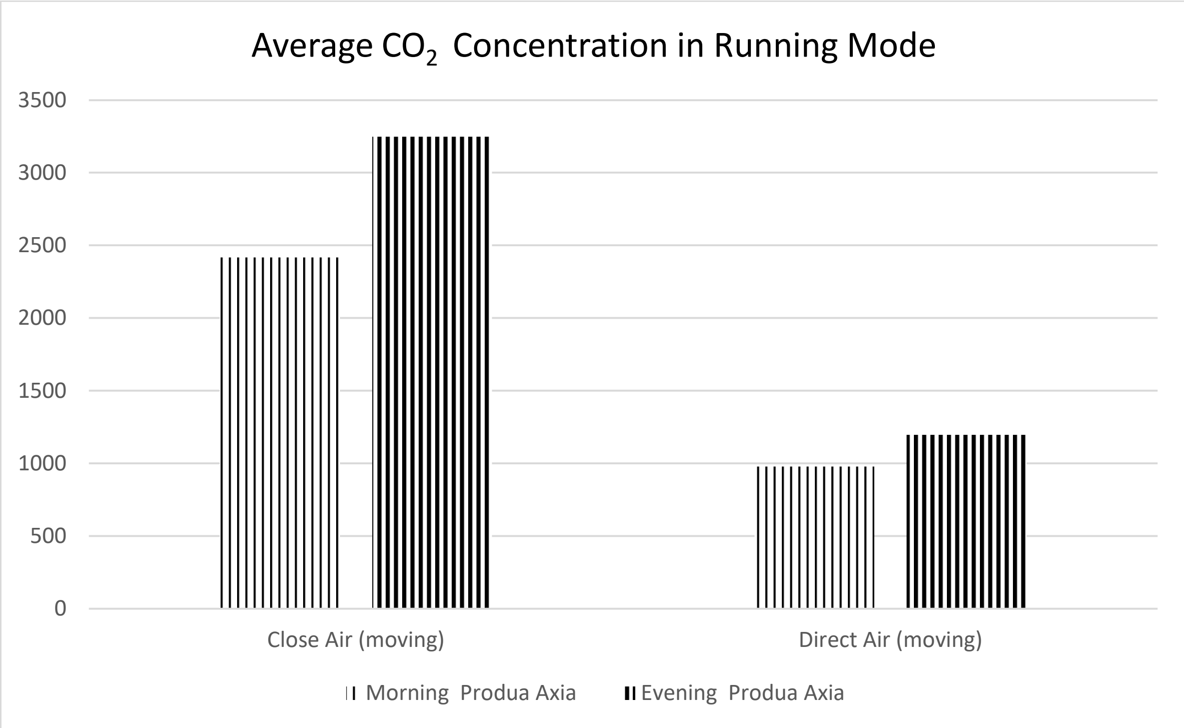

Figure 11. Average CO_2 concentration in Running Mode

5. Conclusion

The results across static and running conditions during both morning and afternoon periods clearly demonstrate that direct air (fresh air intake) mode is significantly more effective than closed air (recirculation) mode in controlling in-cabin CO_2 levels. In static morning and afternoon scenarios, closed air mode leads to rapid and sustained CO_2 accumulation, often exceeding 1000–2500 ppm and occasionally reaching levels above 5000 ppm, which are linked to drowsiness, cognitive decline, and health risks (Satish et al., 2012). This effect is intensified in the afternoon due to increased metabolic output and HVAC limitations in managing both temperature and air quality (El-Fadel & Abi-Esber, 2009). In contrast, direct air mode consistently maintains CO_2 levels below 1000 ppm, aligning with ASHRAE and SAE standards and ensuring better ventilation and occupant alertness, even when accounting for urban air pollutants (Barnes et al., 2018). Overall, the proper ventilation practices in ensuring in-cabin air quality (Jayeoba & Awojobi, 2024). Fresh air intake, particularly during vehicle motion, is the most effective strategy to control CO_2 buildup. Incorporating automatic air exchange systems or CO_2 sensors in vehicle design could significantly improve both occupant health and travel safety. Regardless of time of day or vehicle motion, direct air mode provides superior air quality, reducing health and safety risks associated with CO_2 buildup inside vehicle cabins.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the author(s) used OpenAI's ChatGPT to assist in improving the readability and language of the text. All content generated by ChatGPT was subject to thorough review, editing, and revision by the author(s) to ensure its accuracy, completeness, and alignment with the research objectives. The author(s) take full responsibility for the integrity and content of the published work. This declaration complies with ICGESD 2025 guidelines on the use of generative AI in scientific writing.

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