Experimental Assessment of In-Cabin Air Quality in A Real Vehicle: Effects of Interior Materials, Fragrance, Solar Control Film and Passive Ventilation

Dr. Prasanth K[1], Nandu S[2], Abhinav Shaiju[3], Anjal C. S.[4], Arun Prakash[5], Joseph Benny[6], Krishnaraj P. R.[7]

[1]*Principal, Holy Grace Academy of Engineering, Mala, Thrissur, Kerala, India*

[2]*HOD, Department of Mechanical Engineering, Holy Grace Academy of Engineering, Mala, Thrissur, Kerala, India*

[3,4,5,6,7]*Mechanical Engineering Graduates, Department of Mechanical Engineering, Holy Grace Academy of Engineering, Mala, Thrissur, Kerala, India*

***Abstract*—Vehicle cabins are confined microenvironments in which solar heating, interior materials, aftermarket accessories and ventilation can influence pollutant accumulation. This paper consolidates two complementary experimental studies carried out using a 2009 Maruti Suzuki Zen Estilo to develop and evaluate a realistic in-cabin environmental test platform. The first study established the experimental configuration using three seat-cover conditions—stock fabric, laminated velvet and rexine—together with nano-ceramic solar-control films and a portable multi-parameter air-quality monitor. The second study extended the platform to quantitative evaluation of total volatile organic compounds (TVOC), formaldehyde (HCHO), carbon dioxide (CO_2), carbon monoxide (CO), particulate matter and cabin temperature under heat-soak conditions.**

Peak values in the combined dataset show that the most pronounced TVOC and HCHO readings occurred for the rexine-plus-perfume condition without cooling film, reaching 0.682 mg/m³ and 0.142 mg/m³, respectively. A reference test with the windows opened by approximately 1 inch recorded 0.009 mg/m³ TVOC and 0.004 mg/m³ HCHO. The observations indicate that interior material choice and fragrance use can materially change measured cabin pollutant levels, while passive air exchange substantially reduces accumulation. The study also shows that solar-control film alone does not eliminate pollutant build-up during prolonged parking. Because the experiments were performed on one vehicle under limited environmental conditions using a portable detector, the results should be interpreted as experimental observations rather than universal exposure estimates.

***Index Terms*—vehicle cabin; TVOC; formaldehyde; indoor air quality; seat cover; car perfume; nano-ceramic film; passive ventilation; heat soak**

I. INTRODUCTION

Air quality inside passenger vehicles is influenced by the interaction of cabin geometry, ventilation, solar loading and materials used within the passenger compartment. When a vehicle is parked with the windows closed, solar energy entering through the glazing can raise the temperature of interior surfaces and cabin air. Interior polymers, fabrics, adhesives and accessories may then contribute to volatile emissions. Previous work cited in the source studies associates temperature, material type and ventilation with changes in in-vehicle pollutant concentrations [1–10].

A practical difficulty in vehicle-cabin research is reproducing the thermal and material conditions of an actual passenger compartment. Laboratory chambers provide control but may not reproduce the geometry, glazing area, surface arrangement and natural solar exposure of a vehicle. The first study addressed this issue by converting an actual 2009 Maruti Suzuki Zen Estilo into a repeatable experimental platform. The cabin was evaluated with stock laminated cotton, laminated velvet and rexine seat conditions, with and without ceramic solar-control film, while a portable air-quality monitor was retained at a consistent position. The second study used the same

experimental concept to perform quantitative measurements of TVOC, HCHO, CO_2, CO, particulate matter, temperature and humidity.

The objective of the present consolidated paper is therefore to integrate the platform-development and quantitative-evaluation stages into a single experimental framework. Specific objectives were to (i) establish a realistic vehicle-cabin test environment; (ii) compare the measured response associated with different seat-cover conditions; (iii) examine the influence of a commonly used car fragrance; (iv) examine the role of nano-ceramic solar-control film; and (v) assess the effect of a small window opening as a passive ventilation condition.

II. RELATED WORK

The literature reviewed in the two source studies consistently identifies temperature and interior-material characteristics as important variables in vehicle-cabin emissions. Xiong et al. [1] examined temperature-dependent VOC emissions from vehicle interior materials, while Zhao et al. [2] considered solar radiation and pollutant accumulation during vehicle parking.

Besis et al. [3] investigated VOC concentrations in passenger vehicles and associated exposure considerations. Wang et al. [4] examined formaldehyde emissions from automotive interior materials under elevated temperatures. Hafs et al. [5] investigated TVOC and particulate-matter distribution in vehicle cabins. Other cited studies considered VOC emissions from polymeric materials, human exposure, overall, in-vehicle air quality, temperature-driven emission modelling and solar-control films [6–10].

The combined source material suggests a practical gap between controlled material-emission studies and measurements made in a complete passenger-car cabin. The present work addresses this gap at an experimental-platform level by retaining actual cabin geometry and then systematically varying selected interior conditions.

It does not attempt to represent every vehicle type or every real driving situation; instead, it provides a repeatable test configuration for comparative observations.

III. MATERIALS AND EXPERIMENTAL METHOD

3.1 Experimental Vehicle and Cabin Configuration

A 2009 Maruti Suzuki Zen Estilo hatchback was used as the experimental vehicle. The cabin was selected because it provided a complete passenger compartment with windshield, side glazing, rear glazing, dashboard and seating surfaces while remaining practical for repeated testing. The dashboard and major original interior components were retained. Three seat-cover configurations were considered: the original stock laminated-cotton condition, laminated velvet with cloth, and rexine. Only one seat-cover condition was maintained during an individual test configuration to reduce cross-condition interference.

3.2 Solar-Control Film

Nano-ceramic solar-control film was installed on the glazing. CS80 was used on the front windshield and CS50 on the side and rear glazing. The reported specifications were 76% visible-light transmission, 84% infrared rejection and 50% total solar-energy rejection for CS80, and 50% visible-light transmission, 88% infrared rejection and 59% total solar-energy rejection for CS50. The film condition was therefore treated as a cabin-level thermal-control variable rather than as an independent pollutant source.

3.3 Instrumentation

A portable air-quality detector was positioned centrally and kept at the same location across the test configurations. The reported measurement ranges were 0–999 µg/m³ for $PM_{2.5}$, $PM_{1.0}$ and PM_{10}; 400–5000 ppm for CO_2; 0–999 ppm for CO; 0–9.99 mg/m³ for HCHO; and 0–9.99 mg/m³ for TVOC. Cabin temperature and relative humidity were also recorded. The detector was powered by an internal 2000 mAh lithium battery during heat-soak observations.

3.4 Fragrance and Thermal Conditions

Car perfume was included to represent a common aftermarket cabin accessory.

The source report states that two spray presses were applied for each perfume condition, with approximately 0.10 mL per spray. Tests were performed with the vehicle exposed to direct sunlight

and the windows closed during the principal heat-soak condition. A separate reference condition used approximately 1-inch opening of all four windows to introduce passive air exchange.

3.5 Experimental Matrix

Seat condition	Perfume	Cooling film	Peak TVOC (mg/m³)	Peak HCHO (mg/m³)	Maximum cabin temperature (°C)
Stock fabric	No	No	0.012	0.004	43
Stock fabric	Yes	No	0.022	0.006	43
Stock fabric	No	Yes	0.010	0.003	41
Stock fabric	Yes	Yes	0.027	0.007	43
Rexine	No	No	0.027	0.008	43
Rexine	Yes	No	0.682	0.142	40
Rexine	No	Yes	0.022	0.006	42
Rexine	Yes	Yes	0.032	0.007	42
Laminated velvet	No	No	0.018	0.006	41
Laminated velvet	Yes	No	0.036	0.013	41
Laminated velvet	No	Yes	0.015	0.005	43
Laminated velvet	Yes	Yes	0.328	0.058	45

IV. RESULTS

4.1 Effect of Seat-Cover Material

The no-perfume/no-film observations provide the most direct baseline comparison among the seat-cover conditions. Stock fabric showed a peak TVOC value of 0.012 mg/m³, compared with 0.027 mg/m³ for rexine and 0.018 mg/m³ for laminated velvet. The corresponding reported HCHO values were 0.004, 0.008 and 0.006 mg/m³, respectively, although the stock and laminated-velvet HCHO baselines are marked as extrapolated in the source table. These observations are consistent with the experimental premise that different interior surface materials can produce different cabin-air responses during heat exposure.

4.2 Effect of Car Perfume

The largest TVOC and HCHO peaks in the observation matrix occurred when rexine was combined with perfume without cooling film. TVOC increased from 0.027 mg/m³ in the corresponding no-perfume rexine condition to 0.682 mg/m³ with perfume. HCHO increased from 0.008 to 0.142 mg/m³.

Laminated velvet with perfume also produced elevated peaks, reaching 0.328 mg/m³ TVOC and 0.058 mg/m³ HCHO. The measurements therefore identify fragrance application as an important experimental variable in this cabin configuration.

4.3 Effect of Nano-Ceramic Film

The cooling-film condition produced a mixed response. With no perfume, the reported maximum cabin temperature was reduced for the stock configuration from 43°C to 41°C, while rexine and laminated velvet showed maximum temperatures of 42°C and 43°C, respectively.

The film did not eliminate pollutant accumulation when perfume was present. For rexine with perfume, the reported TVOC and HCHO peaks with film were 0.032 and 0.007 mg/m³, respectively; for laminated velvet with perfume, the values were 0.328 and 0.058 mg/m³.

The source study therefore treats the film as a solar/thermal-control measure rather than a complete emission-control method.

4.4 Effect of Passive Ventilation

The separate ventilation reference test used rexine, perfume and cooling film while lowering all four windows by approximately 1 inch.

The reported peak TVOC was 0.009 mg/m³ and peak HCHO was 0.004 mg/m³, with a maximum cabin temperature of 41°C.

These values were substantially lower than the sealed-cabin rexine-plus-perfume condition and demonstrate the strong influence of air exchange on pollutant accumulation within the tested vehicle.

4.5 Comparison with Reported Guideline Values

Parameter	Maximum reported value	Reference value used in source report	Source report interpretation
TVOC	0.682 mg/m³	<0.500 mg/m³	Exceeds cited value
HCHO	0.142 mg/m³	<0.100 mg/m³	Exceeds cited value
CO_2	2167 ppm	<1000 ppm	Exceeds cited value
$PM_{2.5}$	184 µg/m³	<60 µg/m³ (24 h)	Exceeds cited value
CO	0 ppm	<2 mg/m³ (1 h)	Within cited value

The consolidated experiments indicate that cabin air quality is governed by interacting thermal, material and ventilation effects rather than by a single modification. The real-vehicle platform is important because the glazing, cabin volume, dashboard and seating arrangement remain physically integrated. This provides a more representative environment than an isolated material sample while retaining the ability to vary selected interior parameters.

Among the tested variables, fragrance application produced the most pronounced peaks in the reported TVOC and HCHO dataset. The result does not establish the chemical identity or toxicological significance of individual compounds because the detector reports aggregate parameters rather than a laboratory chromatographic speciation of VOCs. Accordingly, the results are best interpreted as changes in measured TVOC and HCHO under the specified experimental conditions.

The cooling film reduced or moderated some thermal responses but did not consistently suppress pollutant concentrations under all tested configurations. This is physically consistent with the distinction between reducing solar heat input and removing pollutants that are already present in a closed cabin. The ventilation reference condition provides a complementary mechanism: instead of primarily modifying heat input, it increases air exchange and therefore can reduce accumulated concentrations.

The results should nevertheless be interpreted within the experimental limitations. Only one vehicle model was studied, the environmental conditions were not fully controlled, the observation duration was limited, and the portable detector was not described in the source reports as having been independently validated against a laboratory reference method. The presence of extrapolated baseline values in part of the observation matrix further limits quantitative statistical interpretation. These factors prevent broad generalization to all passenger vehicles.

VI. LIMITATIONS AND FUTURE WORK

The study was limited to a single 2009 hatchback and three seat-cover configurations. It did not systematically vary occupant load, HVAC operation, fresh-air/recirculation mode, ambient humidity, exterior colour, parking orientation, vehicle segment or long-term material ageing. Future work should repeat the experiments across multiple vehicles and environmental conditions, use calibrated reference instrumentation, increase the number of independent repetitions, and report uncertainty and statistical significance. Laboratory chemical analysis such as GC-MS could also be used to identify individual VOC species rather than relying only on aggregate TVOC readings. Dynamic driving tests and controlled HVAC experiments would further extend the practical relevance of the platform.

VII. CONCLUSION

This consolidated study combines the development of a realistic automobile-cabin experimental platform with quantitative evaluation of in-cabin pollutant accumulation. A 2009 Maruti Suzuki Zen Estilo was configured with three seat-cover conditions, nano-ceramic solar-control film, a commonly used car fragrance and a multi-parameter air-quality detector. The reported observations show clear differences among interior configurations. The highest measured TVOC and HCHO values in the test matrix were 0.682 mg/m³ and 0.142 mg/m³ for the rexine-plus-perfume condition without cooling film. The separate passive-ventilation test, using approximately 1-inch window openings, recorded 0.009 mg/m³ TVOC and 0.004 mg/m³ HCHO under the specified configuration.

The combined evidence supports three engineering observations within the limits of the experiment: interior material selection affects measured cabin pollutant levels; fragrance application can produce substantial TVOC and HCHO peaks; and passive air exchange can strongly reduce pollutant accumulation in a parked, heated cabin. Solar-control film provides

thermal and solar-control benefits but should not be treated as a standalone substitute for ventilation. Further work using calibrated instrumentation, repeated experiments, additional vehicle types and chemical-speciation methods is required before the findings can be generalized or used for formal exposure-risk assessment.

REFERENCES

[1] J. Xiong, R. Zhang, H. Wang, and S. Huang, "Temperature-dependent emission characteristics of volatile organic compounds from vehicle interior materials," *Building and Environment*, vol. 207, Art. no. 108425, 2022.

[2] P. Zhao, Y. Li, C. Chen, and Y. Zhang, "Impact of solar radiation on pollutant accumulation in vehicle cabins during parking conditions," *Atmospheric Environment*, vol. 246, Art. no. 118071, 2021.

[3] A. Besis, C. Samara, D. Voutsa, and E. Manoli, "Characterization of volatile organic compounds in passenger vehicle cabins and associated exposure risks," *Environmental Pollution*, vol. 330, Art. no. 121763, 2023.

[4] M. Wang, X. Zhang, H. Wang, and J. Xiong, "Formaldehyde emission behavior of automotive interior materials under elevated temperature conditions," Building Simulation, vol. 17, no. 5, pp. 1123–1135, 2024.

[5] N. Hafs, M. Djeddou, A. Benabed, and A. Mehel, "Experimental investigation of TVOC and particulate matter distribution inside a car cabin," Air, vol. 1, no. 3, pp. 184–195, 2023.

[6] G. D. Nielsen, S. T. Larsen, O. Olsen, and L. K. Poulsen, "Emission of volatile organic compounds from plastic-based interior materials used in vehicles," Building and Environment, vol. 170, Art. no. 106599, 2020.

[7] H. Fromme, T. Lahrz, M. Piloty, and H. Gebhart, "Exposure to volatile organic compounds inside vehicle cabins and related health implications," International Journal of Environmental Research and Public Health, vol. 16, no. 13, Art. no. 2441, 2019.

[8] G. Zhang, B. Li, and J. Xie, "A review of in-vehicle air quality research: Pollutant sources, exposure levels, and influencing factors," Indoor Air, vol. 31, no. 6, pp. 1713–1730, 2021.

[9] Z. He, H. Wang, P. Zhang, and J. Xiong, "Modeling temperature-driven VOC emissions from vehicle interior materials under simulated cabin environments," Environment International, vol. 142, Art. no. 105817, 2020.

[10] D. Li, L. Yang, and Y. Huang, "Influence of solar control window films on vehicle cabin thermal load and indoor air quality," Energy and Buildings, vol. 258, Art. no. 111860, 2022.

[11] M. Scheytt et al., "Vehicle Interior Air Quality Testing and Standards," AVL Analytical Technologies, 2025. [Bibliographic details should be verified against the original source before submission.]

[12] M. Wang et al., "Impact of Interior Material Selection on Formaldehyde Concentration in Vehicle Cabins," *Building Simulation*, 2025. [Bibliographic details should be verified against the original source before submission.]

[13] B. Xu, "Air Quality inside Motor Vehicle's Cabins—A Comprehensive Review," *Indoor and Built Environment*, 2018. [Bibliographic details should be verified against the original source before submission.]