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A QUALITATIVE ANALYSIS OF INDOOR AIR QUALITY POLLUTANTS INSIDE A PRIVATE CAR CABIN USING RESPONSE SURFACE METHODOLOGY

Summary

Indoor air quality (IAQ) plays a significant role in our daily life. IAQ is not only important in interior buildings but is also essential to the low volume space of automobile compartments. This study investigates the three critical IAQ pollutants of CO_2, $PM_{2.5}$, and PM_{10} in an air-conditioned private car cabin. Three qualitative input factors of human load, route, and air conditioning (ON and OFF) were considered to evaluate the effect of in-cabin car pollutants. Analysis of variance (ANOVA) was applied to determine the effect of the input parameters that affect IAQ in the car cabin. A mathematical modelling of response factors (pollutants) was determined using response surface methodology (RSM) in connection with the Taguchi orthogonal test design. It was found that indoor car cabin CO_2, $PM_{2.5}$, and PM_{10} concentrations were 3.32, 1.35, and 1.33 times higher than the on-road concentrations, respectively. The air-conditioning input factor has more effects for in-cabin pollutants compared with the other two input factors of human load and route. The R^2 values obtained were greater than 95% for all the response factors. According to the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) standard limit, the air supply flow rate of 7.64 l/s per human (maximum 4 human load) was not enough to keep CO_2 concentrations below 1000 ppm in the currently tested car cabin.

Key words: *indoor air quality, car cabin, particulate matter, indoor pollutant, RSM, ANOVA*

1. Introduction

Day by day, the number of car commuters has been growing steadily, particularly in urban areas. This requires automotive manufacturers to provide better indoor air quality (IAQ) in vehicle compartments. The primary IAQ pollutants inside the car cabin are carbon dioxide (CO_2), fine particulate matter ($PM_{2.5}$), and coarse particulate matter (PM_{10}).

Generally, the accepted indoor CO_2 level should be below 1000 ppm inside buildings for good health conditions. When the CO_2 level rises above the threshold limit of 1000 ppm, it causes headaches, dizziness, and unconsciousness [1]. The aerodynamic diameter of inhalable

PM_{10} coarse particles is 2.5 μm to 10 μm, which can cause either heart or lung disease, nonfatal heart attacks, irregular heartbeat, decreased lung function, and increased respiratory symptoms [2]. The aerodynamic diameter of fine particles of $PM_{2.5}$ is 1 µm to 2.5 µm. These particles that may contain a high amount of numerous toxic metals can readily penetrate the respiratory tract [3]. In the past decades, very few studies have been conducted on IAQ pollutants ($PM_{2.5}$, PM_{10}, and CO_2) in various transport modes [4-7]. Pollutant studies inside vehicle cabins have revealed that exposure to airborne particles could cause sensory irritation, memory impairments, cardiovascular diseases, and respiratory and asthma problems [8-10].

Approximately 10 to 50% of commuters are exposed to in-vehicle ultra-fine particles from road traffic in Los Angeles, California [11]. Car commuters in European cities are exposed to higher levels of PM pollutants than commuters in other kinds of transport [12]. CO_2 concentrations assessed inside a heated car cabin with three input factors of human load, air circulation mode, and heating time revealed that the average CO_2 emissions for two passengers are 1.24 times higher than for one passenger [13]. It was found that to keep the CO_2 level below 1000 ppm, an air temperature not higher than 26ºC and relative humidity below 60% provide better human comfort inside an air-conditioned car cabin with input factors of human load, fresh air supply, and air velocity using multi-objective genetic algorithm (MOGA) techniques [14]. To find the productivity rates in automotive assembly workstations, the Taguchi method was used to optimize environmental factors, such as illuminance, relative humidity, and wet bulb globe temperature (WBGT) [15].

The predicted mean vote (PMV) feedback controller gives better results than simplified temperature feedback in an automobile cabin. The genetic algorithm (GA) is also employed to improve the performance of the fuzzy controller for energy savings and human thermal comfort [16]. To optimize the concentrations of CO_2 and CO (carbon monoxide) in an air-conditioned bus, regression trees and analysis of variance (ANOVA) statistical technique tools are used with the influential parameters of passenger ridership, month, ambient temperature, indoor RH, and ambient RH [17]. Using the response surface methodology (RSM) tool, it was found that the best human comfort conditions were 45% fresh air supply and 6 m/s of air velocity in the air-conditioned car cabin [18].

Past IAQ pollutant studies in car cabins were mostly carried out in a stationary rather than in a driving condition and the results were obtained from a simple descriptive statistical analysis. This is the first car commuter IAQ pollutant study over different routes of Salem City using optimization techniques. Mathematical modelling of the IAQ pollutants of CO_2, $PM_{2.5}$, and PM_{10} connected with the input factors of human load, route, and air conditioning (ON/OFF) was developed. It was found that, according to the ASHARE criterion, the current tested car cabin required a higher rate of outdoor air supply to keep the CO_2 concentration below 1000 ppm.

2. Materials and methods

2.1 Experiment locations

All the test runs were carried out on different routes of Salem City (11.6643ºN, 78.1460ºE), which is located in the State of Tamil Nadu, India. Salem has the sixth-largest population of more than 100,000 people among the 32 urban agglomerations [19]. The city covers an area of 124 km^2 and has thirty-one large scale industries in and around the Salem perimeter. The city is also referred to as ‘Steel City’ because of the Salem steel plant, a unit of the Steel Authority of India (SAIL), which produces hot-rolled stainless steel. The geographical map of the selected test routes is shown in Fig (1). Among many traffic routes in Salem City, the four primary peak hour traffic routes were chosen to study the IAQ in a car cabin. The details of the selected four routes are given in Table 1 with average on-road concentrations. The on-road concentrations were measured while driving a motorcycle on the predefined routes. All the tests were carried out during the winter month of November 2019 in the evening rush hour (4 p.m. to 6 p.m.). In India, PM concentrations are mostly higher during the post-monsoon and winter season.

Fig. 1 Geographical map of the selected traffic routes in Salem City with directions.

Table 1 Four different selected traffic routes in Salem City with average on-road concentrations.

Route No.	Route	Total distance (km)	CO_2 (ppm)	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)
1	Sona College of Technology bus stop to Hasthampatty roundabout	3.9	420	63.40	151.57
2	Hasthampatty roundabout to Thiruvalluvar statue	2.8	401.63	57.54	122.52
3	Thiruvalluvar statue to 3 Roads bus stop	4.4	418.87	77.96	165.75
4	3 Roads bus stop to Sona College of Technology bus stop	3.1	407.29	46.36	89.46

2.2 Measurements

A five-seat sedan car was selected to study the IAQ pollutants. It is a petrol engine type with a displacement of 998 cm^3 and is a right-hand drive, 2012 year model. In the test runs with air conditioning ON, the fan speed was set at a moderate position of 2 from the available settings of 1 to 4. The knob was set to fresh air supply mode rather than the recirculation mode. However, during the test runs of the air-conditioned car in the OFF condition, the windows were fully open.

Two real-time portable handheld devices were used to measure the response factors of CO_2, $PM_{2.5}$, and PM_{10}. An IAQ monitor (model 3007R; Rave Innovations, OKHLA Phase 2, New Delhi, India) was used to measure the $PM_{2.5}$ and PM_{10} pollutants as shown in Fig (2a). It works on the principle of the light scattering method. The range of the IAQ 3007R device is 0 to 1000 μg/m^3 and 0 to 500 μg/m^3 for PM_{10} and $PM_{2.5}$, respectively, with a resolution of 1 μg/m^3 for both pollutants. The Extech instrument (model CO250; FLIR Commercial Systems Inc., Nashua, NH, USA) was used to measure the CO_2 concentrations as shown in Fig (2b). It functions under the principle of the non-dispersive infrared (NDIR) method. The range of the CO250 Extech instrument is 0 to 5000 ppm with a resolution of 1 ppm. Multipoint calibrations of the IAQ 3007R and CO250 Extech portable devices were performed by manufacturers for each factor. The two devices were set to record one-minute time intervals. At the end of each test, the values were sent to the data acquisition system (laptop) for analysis.

The vane anemometer (model 410i; Testo India Pvt., Ltd., Aundh, Pune, India) was used to measure the air flow rate of the inlet ducts as shown in Fig (2c). The measurement range of the Testo 410i anemometer is 0.4 to 30 m/s with a resolution of 0.1 m/s. This device is enabled with a smartphone app and shows the trending graph between air velocity and time. It also gives quick feedback of the multi-point and timed mean calculation of air velocity for various inlet and return ducts. In the selected sedan car, there are four inlet ducts on the front dashboard. Among them, the middle two ducts have a rectangular shape (90 mm × 60 mm) and the other two corner ducts have a circular shape (diameter - 90 mm). The time-averaged air flow rate of the rectangular and circular vents was 24 m^3/h (6.67 l/s) and 31 m^3/h (8.61 l/s), respectively. The average air velocity obtained for the rectangular and circular vents was 2.1 m/s and 2.7 m/s, respectively.

The portable devices of IAQ 3007R and CO250 Extech instruments were placed in the middle back seat of the car cabin for all the test runs. A new air filter was installed in the air-conditioning unit before the commencement of the first test run. To equalize the outdoor concentrations with those in the indoor car cabin, the doors were left fully open for 10 minutes before each test run. The Taguchi test design was used to perform 16 experiments for the given input factors and levels. However, a total of 32 experiments were carried out by repeating each test run twice to ensure standardization of the measurements. A detailed account of the 16 experiments with the average response factors of the selected test runs is given in Table 2.

(a) (b) (c)

Fig. 2 Real-time monitoring handheld devices: (a) Indoor air quality monitor (IAQ 3007R); (b) CO_2 meter (CO250); (c) Vane anemometer (Testo 410i)

2.3 Methodology

This study was divided into three stages. First, the total number of experiments was concluded from the Taguchi standard test design. The Taguchi design suggested the appropriate mixed-level design of an L_{16} orthogonal array. Second, real-time portable devices were used to measure the IAQ response factors inside the car cabin for various input levels of human load, route, and air conditioning. Finally, the obtained results were analysed through Taguchi and response surface methodology (RSM) techniques using DOE software. The complete experimental setup is shown in Fig (3).

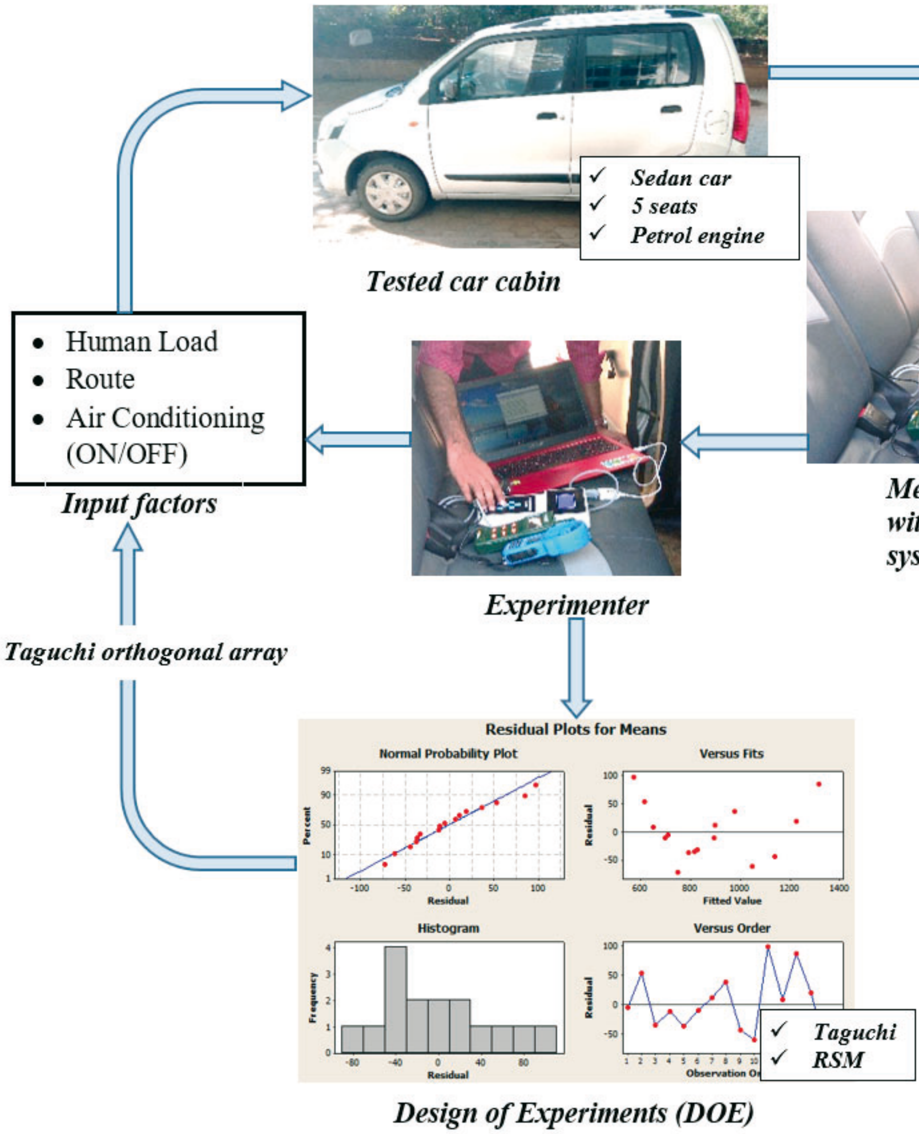

Fig. 3 Experimental setup.

2.4 Taguchi design

All levels of input factors are taken into account equally in the Taguchi design arrays. In this study, an examination was made of the qualitative input factors of human load, route, and air conditioning which may affect the IAQ level inside the car cabin. The input factors of human load and route were taken into consideration as four levels (4^2) and the remaining factor of air conditioning was taken as two levels (2^1), the OFF and ON condition. Therefore, the appropriate mixed-level L_{16} (4^2 2^1) orthogonal array was used in this study. Other lower impact factors may be neglected to reduce the period of testing and to avoid repeating experiments [20-22]. The L_{16} (4^2 2^1) orthogonal array of test runs was carried out in this study with the response factors as given in Table 2. The first column indicates the number of experiments, and the second column shows the corresponding human load with a maximum of four passengers. The third and fourth columns indicate the corresponding four levels of route and the air conditioning setting (OFF (1) and ON (2)), respectively. On the far right of the table, the average response factors of CO_2, $PM_{2.5}$, and PM_{10} are given for the selected test runs.

Table 2 Experimental plan of L_{16} (4^2 2^1) orthogonal test design with average response factors.

Number of test	Qualitative input factors			Response factors		
	Human load	Route	Air conditioning*	CO_2 (ppm)	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)
1	1	1	1	705.18	41.40	88.70
2	1	2	1	671.00	52.20	109.31
3	1	3	2	781.00	21.34	44.44
4	1	4	2	882.73	16.00	33.32
5	2	1	1	755.60	76.34	161.68
6	2	2	1	689.67	104.96	221.19
7	2	3	2	910.88	58.16	121.09
8	2	4	2	1014.00	38.13	79.40
9	3	1	2	1097.89	38.01	79.14
10	3	2	2	987.11	64.29	133.85
11	3	3	1	673.00	105.38	221.45
12	3	4	1	660.20	58.85	125.27
13	4	1	2	1403.80	55.22	114.97
14	4	2	2	1244.62	66.17	137.76
15	4	3	1	679.89	98.14	205.35
16	4	4	1	796.90	67.10	140.39

*Air conditioning 1 - OFF position; Air conditioning 2 - ON position

2.5 Response surface methodology

Response surface methodology (RSM) is a method that develops the mathematical modelling and statistical analysis of responses that are influenced by various levels of input factors (independent variable) [23-25]. This method also helps to discover the existing relationship between the input parameters and responses (dependent variable). In RSM problems, the relationship between the independent variables and responses are solved with the following polynomial second-order equation as shown in eq. (1) [26-28]:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j + \varepsilon \,, \tag{1}$$

where y is the response factor (CO_2, $PM_{2.5}$ and PM_{10}), β_0 is a constant and β_i, β_{ii}, β_{ij}, are the first, second, and interaction input parameters (human loads, routes, and air conditioning). ε represents the noise or error observed in the response y.

2.6 Analysis of variance

Analysis of variance (ANOVA) is a statistical model technique to determine the percentage of the sensitive and non-sensitive effects of the experimental parameters [29-30]. The ANOVA results for the response factors of CO_2, $PM_{2.5}$, and PM_{10} are shown in Tables 3, 4, and 5. The first column represents the regression of linear (human load, route, and air conditioning), square (human load × human load and route × route) and interaction (human load × route, human load × air conditioning and route × air conditioning) terms. However, the square regression term for the air conditioning factor was excluded because of its two levels. The second to sixth column represents the degrees of freedom (DF), sum of squares (SS), the F-test value, the P-value, and the percentage contribution (PC). To ascertain whether the input factors or the responses of interaction are an effect in the ANOVA analysis, the P (importance/probability) value is verified. If a 95% confidence level is considered, then the P-value of $P < 0.05$ states that the factor is in effect. The PC was calculated by the ratio of corresponding SS factors to the total SS.

3. Results and discussion

3.1 ANOVA

The ANOVA results for the CO_2 response factor are given in Table 3. The results show that the air conditioning input factor plays a major role in the CO_2 pollutant with a value of 59.69%. When the ventilation condition is changed from the air conditioning OFF (windows open) to the air conditioning ON (windows closed) position, the accumulation of CO_2 pollutant was high inside the car cabin. Followed by the air conditioning factor, the human load (18% PC) and route (9.29% PC) factors contributed next in order of magnitude. The high value of 86.98% PC was obtained in linear regression rather than in square and interaction regression. Among the interaction parameters of the CO_2 pollutant, human load and air-conditioning interaction regression were more influential (4.82% PC).

Table 3 ANOVA results of CO_2.

Source	DF	SS	F	P	PC (%)
h	1	136451	10.43	0.014	18.00
r	1	70422	5.09	0.059	9.29
a	1	452451	5.55	0.051	59.69
h^2	1	8872	4.14	0.081	1.17
r^2	1	28827	13.45	0.008	3.80
h × r	1	6208	2.90	0.133	0.82
h × a	1	36522	17.04	0.004	4.82
r × a	1	3278	1.53	0.256	0.43
Residual Error	7	15001			1.98
Total	15	758032			100

h: human load; r: route; a: air conditioning; DF: degrees of freedom; SS: sum of squares; F: F-test value; P: P-value; PC: percentage contribution.

Table 4 specifies the ANOVA results for the $PM_{2.5}$ response factor. For the $PM_{2.5}$ pollutant, the air conditioning factor of 35.53% PC was highly influential. Then, the human load (24.21% PC) and route (1.10% PC) factors were followed by the air conditioning factor. Similar to the response factor of CO_2, the input factor of air conditioning was a high contributor to the $PM_{2.5}$ response factor. Table 5 gives the ANOVA results for the PM_{10} response factor. Like $PM_{2.5}$, the PC for PM_{10} is also in the order of air conditioning (36.81%), human load (23.43%), and route (1.13%). The linear regression term contribution was higher, with a value of 61.39% PC for PM_{10}, than the interaction and square regression terms.

Table 4 ANOVA results of $PM_{2.5}$.

Source	DF	SS	F	P	PC (%)
h	1	2599.4	15.69	0.005	24.21
r	1	118.2	1.35	0.283	1.10
a	1	3814.5	10.82	0.013	35.53
h^2	1	1000.9	19.82	0.003	9.32
r^2	1	2015.8	39.92	0.000	18.78
h × r	1	275.4	5.45	0.052	2.57
h × a	1	10.7	0.21	0.660	0.10
r × a	1	547.5	10.84	0.013	5.10
Residual Error	7	353.5			3.29
Total	15	10735.9			100

h: human load; r: route; a: air conditioning; DF: degrees of freedom; SS: sum of squares; F: F-test value; P: P-value; PC: percentage contribution.

Table 5 ANOVA results of PM_{10}.

Source	DF	SS	F	P	PC (%)
h	1	11150.5	15.95	0.005	23.44
r	1	541.4	1.27	0.297	1.14
a	1	17514.2	11.05	0.013	36.81
h^2	1	4517.7	20.45	0.003	9.50
r^2	1	8628.8	39.05	0.000	18.14
h × r	1	1224.9	5.54	0.051	2.57
h × a	1	45.3	0.21	0.664	0.10
r × a	1	2404.8	10.88	0.013	5.05
Residual Error	7	1546.6			3.25
Total	15	47574.3			100

h: human load; r: route; a: air conditioning; DF: degrees of freedom; SS: sum of squares; F: F-test value; P: P-value; PC: percentage contribution.

3.2 Developing the model

The Taguchi method helps to perform meaningful experiments for the given input factors and levels. However, developing the mathematical model for the response factors is not available in the Taguchi method. Hence, the RSM tool was used to develop the quadratic models for the response factors of CO_2, $PM_{2.5}$, and PM_{10} pollutants associated with the input factors of human load, route, and air conditioning. In this study, Minitab 18 software was used to analyse the obtained experimental data. In previous studies, Minitab software was employed to predict the equation for the response factors [31-34]. The second-degree equation for the three input factors is given in eq. (2). By using the input factors, the responses were presented as a predicted model equation. The determined response factors for each regression model and R^2 values are given in Table 6:

$$y=\beta_0+\beta_1 h+\beta_2 r+\beta_3 a+\beta_{11} h^2+\beta_{22} r^2+\beta_{33} a^2+\beta_{12} h\times r+\beta_{23} r\times a+\beta_{13} h\times a, \quad (2)$$

where ‘h’ is the human load, ‘r’ is the route, and ‘a’ is the air conditioning.

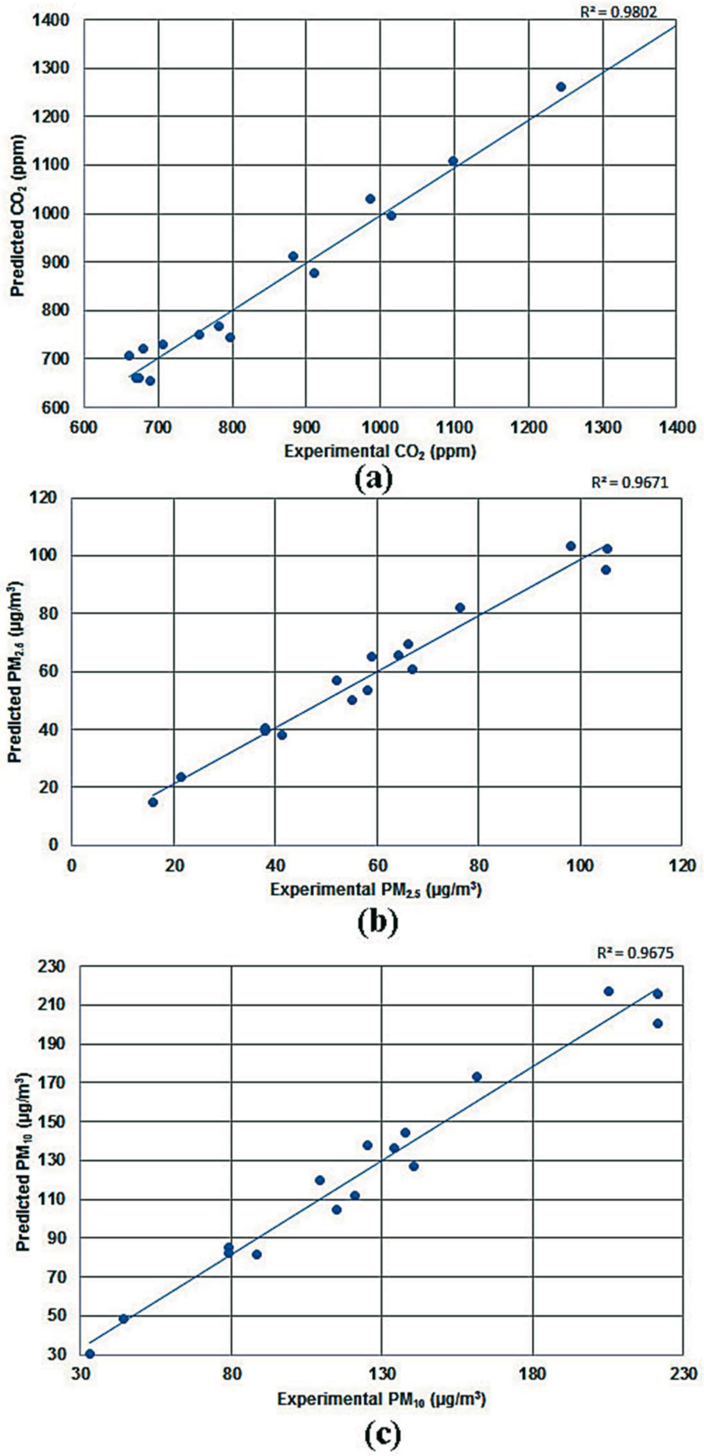

Fig. 4 Comparison of the experimental and predicted values of response factors (a) CO_2, (b) $PM_{2.5}$, and (c) PM_{10}.

Table 6 Regression models and R^2 values.

Regression models	R^2 (%)
$CO_2 = 3268 - 419h - 292r - 975a + 10.47h^2 + 18.87r^2 - 11.67h\times r + 189.9h\times a + 56.9r\times a$	98.02
$PM_{2.5} = 64 + 78.9h + 23.1r - 209a - 3.515h^2 - 4.989r^2 - 2.46h\times r - 3.24h\times a + 23.25r\times a$	96.71
$PM_{10} = 143 + 166.3h + 47r - 442a - 7.47h^2 - 10.32r^2 - 5.19h\times r - 6.7h\times a + 48.7r\times a$	96.75

The coefficient of determination R^2 obtained more than 95% for all the response factors. The response values lie within the valid interval of the prediction values. The actual values are nearest to the prediction values, which is quite sufficient. Fig (4) shows the graphs of correlation between the experimental values and the predicted values of CO_2, $PM_{2.5}$, and PM_{10} response factors.

The marked points on the graphs denote each position where the experimental values are very nearly accompanied by the predicted values. The points approaching the linear curves specify how consistent the estimated values are with the experimental values. In fact, the predicted R^2 values are 98.02%, 96.71%, and 96.75% for the CO_2, $PM_{2.5}$ and PM_{10} pollutants as shown in Fig. 4(a-c), respectively. Hence, from the three graphs, it can be seen that the model response values and the predicted values are very close to the experimental values. Therefore, the results indicate that the quadratic prediction models obtained in accordance with the input factors for CO_2, $PM_{2.5}$, and PM_{10} can be appropriately used in other related models. Thus, the study has contributed to revealing how to predict IAQ pollutants and comfort inside an automobile cabin.

3.3 Response surface models

Two-dimensional contour plots were used to investigate the effects of the input factor level. The plots represent the relationship between two input factors for a single response factor. The globular shape of the response surface in the plots indicates that it is more significant when it looks elliptical or concave anticlinal. The contour plots of the response factors of CO_2, $PM_{2.5}$, and PM_{10} are shown in Figs. (5-7), respectively.

There is no significant correlation between the routes and the human loads for the CO_2 response factor (Fig (5a)). For Route 1 (Sona College of Technology bus stop to Hasthampatty roundabout), the mean CO_2 response factor was higher than for the other three routes. At the time of measurements, bridge construction works were taking place on route 1 between the Five Roads and Hasthampatty roundabout (2 km).

CO_2 concentration accumulation was high when the human load increased and when the ventilation condition was changed from the air conditioning OFF (1) to the ON (2) setting as shown in Fig (5b). The maximum CO_2 concentration (1403.8 ppm) was obtained in human load 4, route 1, and with the air conditioning in the ON position. It was 3.32 times higher than the on-road (route 1) CO_2 concentrations (420 ppm). On the other hand, when the windows were fully closed with the air conditioning in the ON position, the CO_2 concentration buildup was high owing to the increase in the human load. For better human comfort, the ASHRAE standard recommends that the CO_2 concentration inside a building should be less than 1000 ppm, with the lowest outdoor air supply rate of 2.51 l/s per person [35]. Assuming this standard limit for the current tested car cabin, it was observed that, with the exception of human load 1, the CO_2 mean concentration for other human loads exceeded the limit of 1000 ppm with the air conditioning in the ON setting, as shown in Table 2. From the air flow measurement, it was found that the complete air flow rate obtained inside the car cabin was 30.56 l/s, which is the supply rate of 7.64 l/s per person (with a maximum human load of four persons). This shows that the air supply rate is 3.04 times greater than the ASHRAE standard limit. However, this supply rate is not enough to keep the CO_2 accumulation inside a sedan car cabin below 1000 ppm. Introducing extra vents with a high air supply rate may lead to a reduction of the CO_2 concentration in the vehicle cabin. Fig (5d) depicts the effect plots of CO_2 means for individual factors.

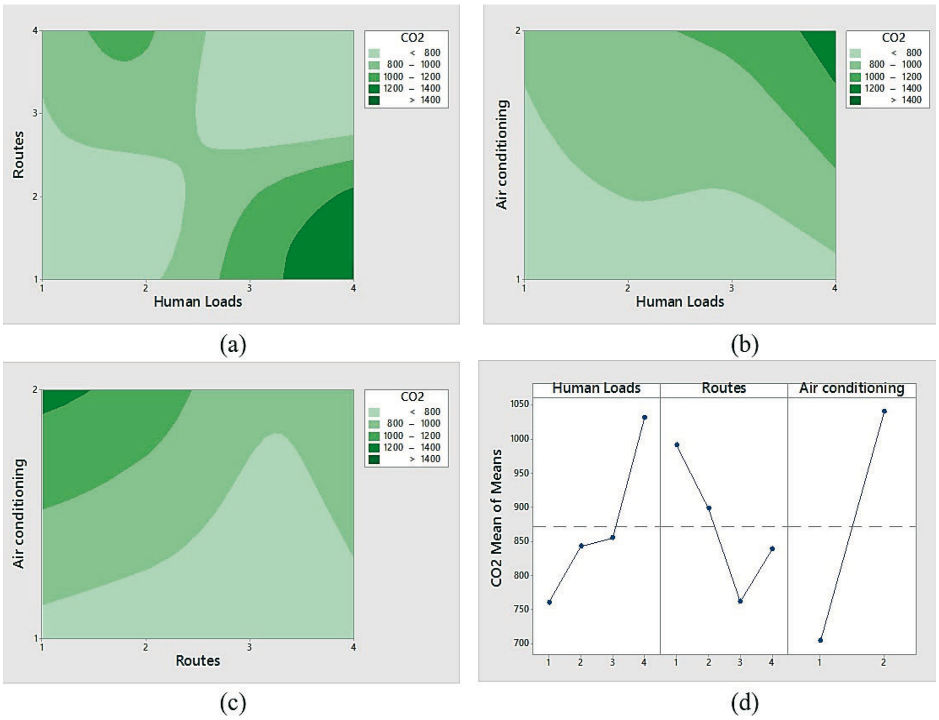

Fig. 5 Contour plots for CO_2 between (a) human load and route, (b) human load and air conditioning, and (c) route and air conditioning. (d) Effects plot for CO_2 means.

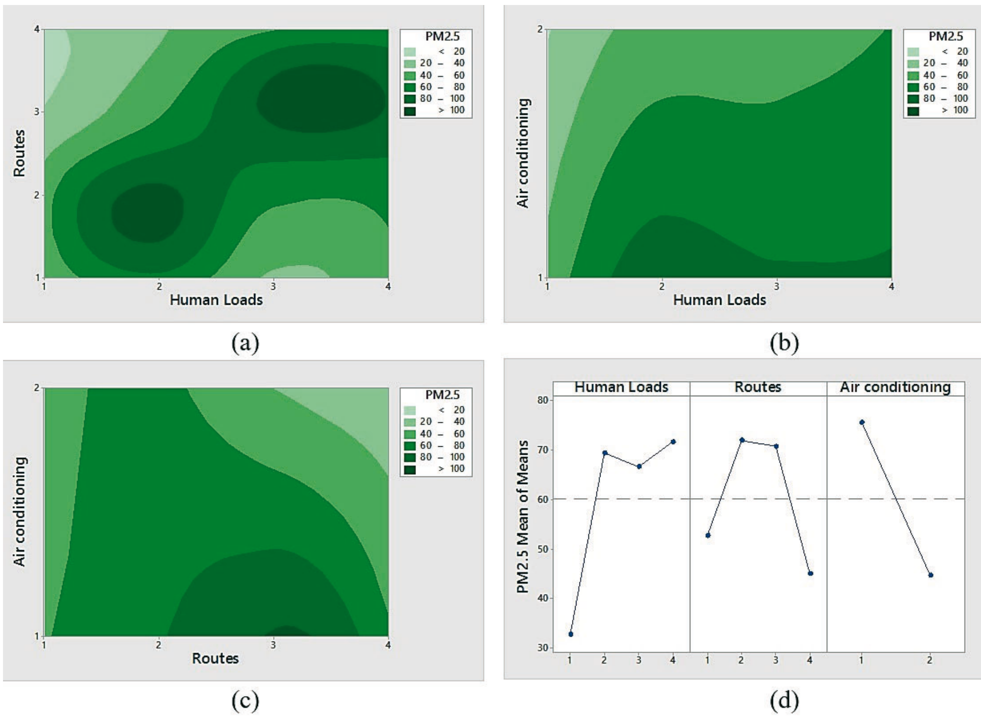

Fig. 6 Contour plots for $PM_{2.5}$ between (a) human load and route, (b) human load and air conditioning, and (c) route and air conditioning. (d) Effects plot for $PM_{2.5}$ means.

In contrast to the CO_2 pollutant, humans were exposed to a high $PM_{2.5}$ concentration when the air conditioning was in the OFF (windows open) position (Fig (6b)). The national central pollution control board (CPCB) recommends a maximum satisfactory limit for $PM_{2.5}$ to be 60 μg/m^3 [36]. Table 1 shows that on routes 1 and 3 (Thiruvalluvar statue to 3 Roads bus stop) the average on-road $PM_{2.5}$ concentration was higher than the CPCB limit. As previously mentioned, bridge construction works were taking place on route 1. Route 3 is the main connecting road for the two biggest bus terminals of Salem City: the new bus stand and the old bus stand. Hence, people's activities are always high on route 3. Accordingly, the highest in-vehicle car cabin $PM_{2.5}$ concentration (105.38 μg/m^3) was recorded on route 3 when the air conditioning was on the OFF setting. It is 1.35 times higher than the on-road $PM_{2.5}$ concentration (77.96 μg/m^3). Fig (6d) shows the graph of the $PM_{2.5}$ mean of means effect. Irrespective of the route and air conditioning factors, human load 1 revealed a mean $PM_{2.5}$ concentration below the satisfactory CPCB limit.

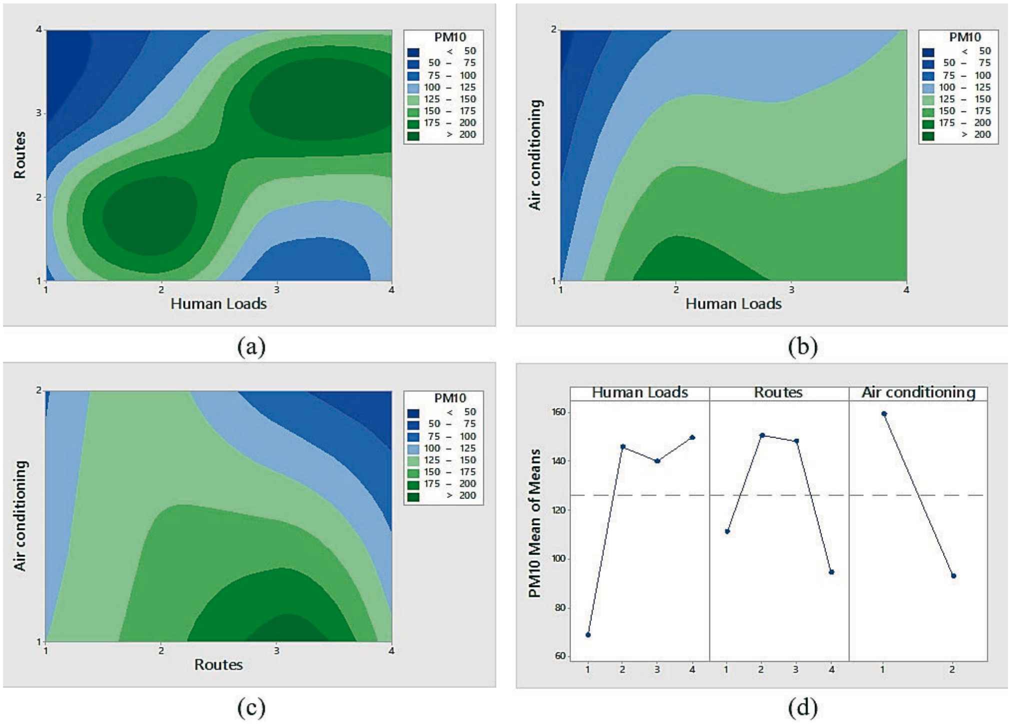

Fig. 7 Contour plots for PM_{10} between (a) human load and route, (b) human load and air conditioning, and (c) route and air conditioning. (d) Effects plot for PM_{10} means.

The contour plots for the PM_{10} concentration are shown in Fig (7). Like $PM_{2.5}$, the effects of varying input factor levels for PM_{10} also obtained the same result. The CPCB suggests that the standard limit for the PM_{10} pollutant to be 100 μg/m^3 for good health [36]. According to the CPCB limit, the PM_{10} concentration was exceeded in the tested car cabin on all the routes except route 4 (3 Roads bus stop to the Sona College of Technology bus stop). This is because route 4 has a low amount of anthropogenic activities such as shops, buildings, etc. The maximum in-vehicle PM_{10} concentration (221.45 μg/m^3) was attained on route 3 with the air conditioning in the OFF ventilation position, which is 1.33 times higher than the on-road PM_{10} concentration (165.75 μg/m^3).

From the results, it can be seen that the IAQ pollutants of CO_2 and particulate matter concentrations could be reduced by increasing the outdoor air supply rate and with the air conditioning in the ON position (windows closed) irrespective of the routes. However, this study was limited to particular IAQ parameters, but in future it is planned to investigate other indoor environmental quality (IEQ) parameters of air velocity, air temperature, relative humidity, the fresh air supply mode, and the recirculation mode. In addition, a comparative study may be made with other different volume automobile cabins such as those of SUVs and MUVs.

4. Conclusions

This study assessed the critical indoor air quality (IAQ) pollutants of CO_2, $PM_{2.5}$, and PM_{10} inside a private car cabin. The summarized results from this study are as follows:

- In the air conditioning ON ventilation position (windows closed), the CO_2 concentration rose beyond the ASHRAE standard limit (1000 ppm) for all human loads except human load 1.
- In contrast to the CO_2 pollutant, humans were exposed to high PM concentrations when the air conditioning was in the OFF ventilation position (windows open).
- The air conditioning factor plays a greater role in relation to IAQ pollutants inside the car cabin with percentage contributions (PC) of 59.69%, 35.53%, and 36.81% for CO_2, $PM_{2.5}$, and PM_{10} concentrations, respectively, than for the other two factors of human load and route.
- The mathematical modelling for IAQ pollutants was developed in association with the input factors of human load, route, and air conditioning.
- The experiment values closer to the prediction values seem to be reasonably satisfactory. Therefore, design of experiments (DOE) and response surface methodology (RSM) tools could help to predict better human comfort inside automobile cabins.
- Finally, irrespective of the routes, commuters can be exposed to acceptable standard limits of CO_2 and particulate matter concentrations by increasing the outdoor air supply rate and by setting the air conditioning to the ON position (windows closed).

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