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A comprehensive evaluation model for the intelligent automobile cockpit comfort

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Under the background of automobile intelligence, cockpit comfort is receiving increasing attention, and intelligent cockpit comfort evaluation is especially important. To study the intelligent cockpit comfort evaluation model, this paper divides the intelligent cockpit comfort influencing factors into four factors and influencing indices: acoustic environment, optical environment, thermal environment, and human–computer interaction environment. The subjective and objective evaluation methods are used to obtain the subjective weights and objective weights of each index by the analytic hierarchy process and the improved entropy weight method, respectively. On this basis, the weights are combined by using the game theory viewpoint to obtain a comprehensive evaluation model of the intelligent automobile cockpit comfort. Then, the cloud algorithm was used to generate the rank comprehensive cloud model of each index for comparison. The research results found that among the four main factors affecting the intelligent automobile cockpit comfort, human–computer interaction has the greatest impact on it, followed by the thermal environment, acoustic environment, and optical environment. The results of the study can be used in intelligent cockpit design to make intelligent cockpits provide better services for people.

Automobiles play a very important role in people's daily lives. With the rapid development of artificial intelligence, internet technologies and communication technologies, intelligent automobiles will occupy an important position and be competitive in the automobile industry¹. Intelligent technologies are rapidly evolving with the help of the latest information technologies, which are turning simple and ordinary automobiles into intelligent automobiles². The development of intelligent automobiles aims to achieve "safe and comfortable next-generation automobiles" that have not only the common features of the automobiles themselves but also the functionality of intelligent technologies³. In the future, autonomous driving technology will change the traditional driving pattern, the driver will be freed from boring driving operations, and the automobile cockpit will become a place for rest, entertainment and work. The main trends in the development of intelligent automobiles are to ensure safety, comfort, efficiency and environmental sustainability⁴. Eventually, with the integration of information and communication technologies, intelligent automobiles will become standardized⁵.

People's demand for comfort in automobiles is increasing, and comfort has become an important factor influencing passengers' choice of intelligent automobiles^{6,7}. For drivers, driving comfort is related not only to satisfaction with the driving experience but also to driving safety and the long-term health of the driver⁸. For passengers, passenger comfort is a major concern for road automobile passengers because it affects people's health and productivity⁹. In the current context, improving driving safety and comfort are very persistent themes with in-automobile design¹⁰. Passenger comfort analysis plays a pivotal role in the automobile evaluation process. Passenger comfort as a subjective perception is a complex term that includes factors such as thermal environment comfort and acoustic environment comfort^{11–13}. Among them, the thermal environment has an impact on the efficiency and comfort of personal travel¹⁴. The acoustic environment has an impact on people performing complex behaviors; noise can cause stress and interfere with attention, and the acoustic environment also affects passengers' cognitive performance¹⁵.

Many factors affect passenger comfort. It has been found that the optical environment affects the physiological and behavioral patterns of occupants. As the primary environmental cue to the body's master biological clock, the optical environment affects sleep, mood, performance, alertness, quality of life, and health in different

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populations^{16–18}. The factors influencing passenger comfort can be considered equally influential for intelligent automobile cockpit comfort¹⁹. Manning et al. in 2021 pointed out that the complexity of human–computer interaction is an important factor in evaluating the layout of intelligent cockpits²⁰. For the detection of passenger comfort, most existing studies focus on physical factors affecting comfort, such as sitting position, vibration and noise, but few scholars have used physiological signals between humans and the driving environment to detect intelligent automobile cockpit comfort²¹. In indoor human comfort evaluation, the acoustic environment, optical environment, and thermal environment are considered the three main physical factors affecting human comfort²². In the evaluation of intelligent automobile cockpit comfort, the scientific and comprehensive selection of indicators has an important influence on the accuracy and objectivity of the evaluation results. Therefore, a multifactor comprehensive evaluation method should be used to comprehensively evaluate the intelligent automobile cockpit comfort from multiple aspects, such as acoustic environment, optical environment, thermal environment, and human–computer interaction.

As the automobile becomes increasingly intelligent, research on the evaluation model of intelligent automobile cockpit comfort is also very important. After the evaluation indices are selected, it is necessary to find a suitable evaluation method for each index weight. To date, the determination of index weights is roughly divided into subjective assignment methods and objective assignment methods^{23,24}. The subjective assignment method is a method in which decision-makers directly give preference information, such as the analytic hierarchy process (AHP), least squares and the Delphi method^{25–27}. The objective assignment method is a method based on the information of the decision matrix, such as the entropy weighting method, multi-objective optimization method, principal component analysis, and the multiple attribute decision-making model (MADM)^{28–31}. Among them, AHP was used to evaluate the relative importance among various services provided by intelligent automobiles, such as driver assistance, infotainment, and IoT hubs³². As a subjective empowerment method, AHP is widely used in multicriteria decision-making and is suitable to help solve decision problems characterized by many interrelated factors^{33,34}. However, the subjective weight determination method has the disadvantage of being influenced by the subjective preferences of decision-makers³⁵. The entropy weight method was used to measure the complexity of human–computer interaction in intelligent cockpits and calculated the weight distribution of specific metrics that affect the complexity of human–computer interaction inside intelligent cockpits²⁰. A multicriteria decision model, as an objective assignment method, was used to evaluate the feasibility and effectiveness of the cockpit ergonomic layout³⁶. In the objective evaluation method, the entropy weight method mainly uses the size of the entropy value in information theory to represent the uncertainty of the message. It can calculate the ability of each evaluation attribute to transmit decision-making information, and calculate the relative weight between attributes^{37–40}. In addition, the entropy method itself has inherent defects, namely: (1) when experts believe that a certain indicator has no impact on the intelligent automobile cockpit comfort, there will be a situation in which the traditional entropy method calculation equation is restricted; and (2) when experts believe that different indicators have the same degree of impact on the intelligent automobile cockpit comfort, there will be a situation in which the entropy value jumps, making the evaluation of the intelligent automobile cockpit comfort unrealistic. Due to these inherent defects, when using the entropy weight method to evaluate the intelligent automobile cockpit comfort, correction coefficients K_1 and K_2 should be introduced to improve the traditional entropy weight method.

The combination weights derived from the game theory-based combination assignment method can take into account the objective properties of the program indicators while fully considering the subjective tendencies of decision-makers. The result of minimizing the deviation of the subjective and objective weights is the result of a Nash equilibrium after a noncooperative game with subjective and objective weights⁴¹. To evaluate the intelligent automobile cockpit more comprehensively, AHP was used to calculate subjective weights, objective weights were calculated using the improved entropy weighting method. And game-theoretic combined weights were introduced to construct a comprehensive evaluation model for the intelligent automobile cockpit comfort.

Materials and methods

Evaluation index system construction. The intelligent automobile cockpit comfort impact evaluation system is complex. Too many or too few indicators are not conducive or do not facilitate the scientific, reasonable, and accurate judgment and evaluation of the system. When there are too few indicators, it is impossible to accurately reflect the judgmental attributes of the system. When there are too many indicators, it will make the judgment attributes of the system too complicated. With the indoor environmental comfort evaluation as a reference, a comprehensive evaluation system for the impact of intelligent automobile cockpit comfort is established according to the ASHRAE standard and the standard proposed by the international standards organization TC205 in 2005, as shown in Fig. 1^{42,43}. The evaluation system includes four primary indicators, i.e., the acoustic environment, optical environment, thermal environment and human–computer interaction, and 14 secondary indicators.

Subjective weights. The steps to calculate the weights using AHP methods are as follows. Step 1: Decompose complex problems into multielement problems. Step 2: Group these elements to create a hierarchical analysis model. Step 3: Construct a judgment matrix A , compare any two elements using the 1–9 scale method, and obtain the importance of each indicator at each level. Step 4: Calculate the maximum eigenvalue vector and subjective weights of the judgment matrix using mathematical methods. Step 5: Based on the consistency index CI calculation, the consistency of the judgment matrix is tested, expressed as $CI = (\lambda_{max} - n)/(n - 1)$, and the average random consistency index RI . If the random consistency ratio $CR = CI/RI < 0.10$, then the consistency of the judgment matrix is considered acceptable; otherwise, the judgment matrix should be appropriately revised.

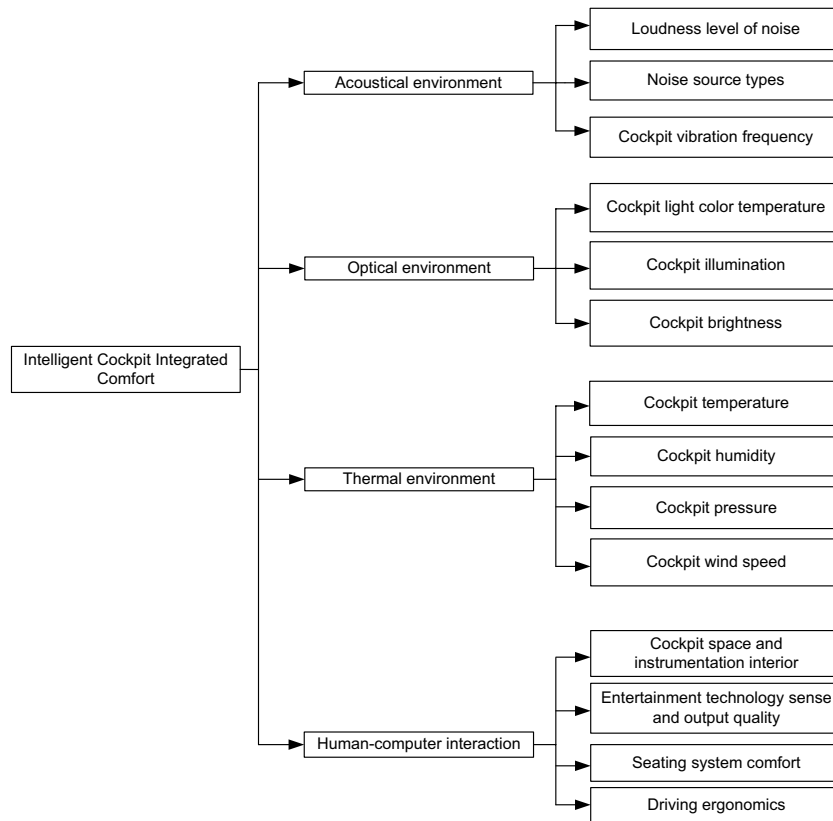


Figure 1. Comprehensive evaluation index system for impact of intelligent automobile cockpit comfort.

Objective weights. The objective weight is calculated by the entropy weight method, and the rating of the j th evaluation index among the i th experts is recorded as x_{ij} when using entropy weight for evaluation. The steps of calculating the objective weights are as follows:

- (1) The weight of the j th evaluation index in the rating value of the i th expert is recorded as p_{ij} , which is calculated as:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}} \tag{1}$$

Since $0 \leq p_{ij} \leq 1$, then $0 \leq -\sum_{i=1}^n p_{ij} \ln p_{ij} \leq 1, 0 \leq H_j \leq 1$. If experts believe that a certain indicator has very little or even no effect on the intelligent automobile cockpit comfort, there will be a case when $p_{ij} = 0$. In this case, $\ln p_{ij}$ is meaningless. Therefore, this paper introduces a correction coefficient K_1 , which modifies the equation as follows:

$$p'_{ij} = \frac{(p_{ij} + K_1)}{\sum_{i=1}^n (p_{ij} + K_1)} \tag{2}$$

Among the models that use the improved entropy weight method in a decision, there is a risk evaluation model based on the improved entropy weight and a decision model in terms of risk evaluation, both of which take the correction coefficient K_1 as 10^{-4} and achieve good evaluation results⁴⁴. Therefore, to correct Eq. (1) in this paper, we take the value of K_1 as 10^{-4} . The introduction of this correction factor K_1 avoids the extreme case where the expert believes that a certain indicator has no effect on the intelligent automobile cockpit comfort and makes $\ln p_{ij}$ meaningless. It solves the limitations of the traditional equation and has less impact on the entropy value H_j .

Calculate the entropy value H_j of the j th indicator:

$$H_j = \frac{1}{\ln(n)} \sum_{j=1}^m p'_{ij} \ln p'_{ij} \tag{3}$$

Calculate the objective weights of the indicators ω_j :

$$\omega_j = \frac{1 - H_j}{\sum_{j=1}^m (1 - H_j)}. \quad (4)$$

This equation has an inherent deficiency. It occurs when experts believe that the degree of influence of each indicator on the intelligent automobile cockpit comfort is very similar, that is, when the weights of the four indicators of acoustic environment, optical environment, thermal environment and human-computer interaction are very close. At this time, when the indicator entropy value H_j is close to 1 ($j = 1, 2, 3, \dots, m$), the small difference between H_j and the others will cause the corresponding entropy weight of each to change exponentially, and the phenomenon of entropy jump occurs, making the intelligent automobile cockpit comfort level not match the actual situation. If a larger positive correction factor K_2 is added to the numerator and denominator at the same time, the above entropy jump phenomenon can be corrected. The entropy weight equation in this case will change to:

$$\omega_j = \frac{1 - H_j + K_2}{\sum_{j=1}^m (1 - H_j + K_2)} (K_2 > 0). \quad (5)$$

K_2 must be considered when taking the value of the entropy change and cannot affect the final established intelligent automobile cockpit comfort evaluation model. In the research model of the importance of network assets based on objective empowerment, K_2 is taken as $\frac{1}{10} \sum_{j=1}^m (1 - H_j)$ and achieves good results⁴⁵. At the same time, it is calculated that it will not have a large impact on the original entropy value. Therefore, to correct Equation (5) in this paper, we take the value of K_2 as $\frac{1}{10} \sum_{j=1}^m (1 - H_j)$.

Combined weights. The subjective weights and objective weights of the intelligent automobile cockpit comfort evaluation index can be calculated by using AHP and improved entropy weight method, respectively. According to the idea of game theory, the subjective and objective weights are fused to seek the optimal solution of the weights and obtain the combined weights of the intelligent automobile cockpit comfort impact evaluation index. The specific steps are as follows. With s methods to assign weights to each evaluation indicator, the s assigning methods obtain the sum of the s evaluation index weight vector:

$$W_k = (W_{k1}, W_{k2} \dots W_{ki}) (k = 1, 2, 3, \dots, s). \quad (6)$$

Any linear combination of the sum of s vectors is given by:

$$W = \sum_{k=1}^s \alpha_k W_k^T (k = 1, 2, \dots, s). \quad (7)$$

Solving for the optimal weight coefficient α_k , for which the countermeasure model is introduced:

$$\min \left\| \sum_{k=1}^n \alpha_k W_k^T - W_l^T \right\| (l = 1, 2, \dots, n) \quad (8)$$

Based on the properties of differentiation, the optimal first-order derivative condition for the above Equation (8) is derived as:

$$\sum_{k=1}^n \alpha_k W_l W_k^T = W_l W_l^T (l = 1, 2, \dots, n). \quad (9)$$

According to Eq. (9), $(\alpha_1, \alpha_2, \dots, \alpha_n)$ can be calculated and then normalized to obtain the weighting coefficients: $\alpha'_k = \alpha_k / \sum_{k=1}^n \alpha_k$. Then, the game-theoretic-based combination weight $W' = \sum_{k=1}^n \alpha'_k W_k^T$, $k = 1, 2, 3, \dots, n$. The final obtained intelligent automobile cockpit comfort evaluation model $W' = \alpha'_1 W_1^T + \alpha'_2 W_2^T$, where α'_1 is the optimal weight coefficient of the AHP method and α'_2 is the optimal weight coefficient of the improved entropy weight method. W_1 is the subjective weight derived using the AHP method, and W_2 is the objective weight derived using the improved entropy weight method.

Principle of cloud model. Li De-Yi et al. proposed a cloud model based on the cross-pollination of probability theory and fuzzy geometry theory. The cloud model uses the three numerical feature values of cloud expectation E_x , entropy E_n and super entropy H_e to react to the uncertainty and vagueness of passenger comfort evaluation, and the transformation of qualitative concepts and quantitative expressions is carried out through the cloud generator⁴⁶. Expectation E_x is the most typical sample point in the passenger comfort evaluation domain, i.e., the mean value of the cloud drops; entropy E_n is the measure of vagueness in passenger comfort evaluation, and the larger its value, the more vaguely the concept is expressed; and super entropy H_e is the uncertainty measure of entropy E_n , i.e., the entropy of entropy, and the larger its value is, the greater the randomness of affiliation, responding to the association of vagueness and randomness.



Figure 2. Interior view of the cockpit of the Xiao-Peng P7 automobile.

	Acoustic environment	Optical environment	Thermal environment	Human-computer interaction
Expert 1	8.1	8.2	8.4	8.5
Expert 2	7.5	7.3	7.6	7.9
Expert 3	8.3	8.2	8.4	9
Expert 4	8.2	7.9	8	8.7
Expert 5	8.4	8.1	8.2	8.7

Table 1. Level 1 index score value.

Comprehensive evaluation level	Intolerable	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Comfortable
Interval	[0, 2)	[2, 4)	[4, 6)	[6, 8)	[8, 10]
E_x	1	3	5	7	9
E_n	0.33	0.33	0.33	0.33	0.33
H_e	0.05	0.05	0.05	0.05	0.05

Table 2. Standard evaluation level numerical characteristics.

Intelligent automobile cockpit comfort evaluation example study

Expert evaluation. As a powerful intelligent automobile, the Xiao-Peng P7 has the four highlights of self-driving, human-machine interaction, the Internet of Everything and intelligent ecology and is considered the new standard for the second generation of intelligent automobiles in China; it is shown in Fig. 2. Five experts in the automobile field were invited to evaluate the intelligent cockpit comfort of the Xiao-Peng P7 based on different indicators reflecting their usual work and automobile riding experience. Based on a 10-point scale, and the higher the score, the greater the impact, the scoring results are shown in Table 1.

Determination of subjective weights. The questionnaire was used to investigate the importance of each indicator in the criterion layer, and then the judgment matrix A was obtained:

$$A = \begin{bmatrix} 1 & 1.19 & 0.89 & 0.78 \\ 0.84 & 1 & 0.53 & 0.60 \\ 1.12 & 1.88 & 1 & 0.81 \\ 1.27 & 1.66 & 1.24 & 1 \end{bmatrix}$$

After calculating the maximum eigenvalue of the judgment matrix A : $\lambda_{\max} = 4.0159$, the consistency index $CI = 0.0053$. Table 2 shows the average random consistency index $RI = 0.89$, the consistency ratio $CR = 0.0059 < 0.10$, and the consistency ratio of the judgment matrix is acceptable. The subjective weight is $\omega_1 = (0.2337, 0.1762, 0.2792, 0.3109)$.

Determination of objective weights. By the improved entropy weight method, the objective weight is calculated by substituting the score value of the first-level index into Equations (1)–(5), which is recorded as ω_2 , by calculating the objective weight: $\omega_2 = (0.2383, 0.2707, 0.2192, 0.2719)$.

Determination of combination weights. Using the idea of combining weights from game theory, the index weights obtained from AHP and the entropy weight method are combined to obtain the optimal weight coefficients $\alpha_1 = 0.7944$ and $\alpha_2 = 0.2168$. These coefficients are then normalized, leading to $\alpha'_1 = 0.7872$ and $\alpha'_2 = 0.2128$. Using the equation $W' = \alpha'_1 W_1^T + \alpha'_2 W_2^T$, the final combined weight $W' = (0.2347, 0.1963, 0.2664, 0.3026)$ is obtained.

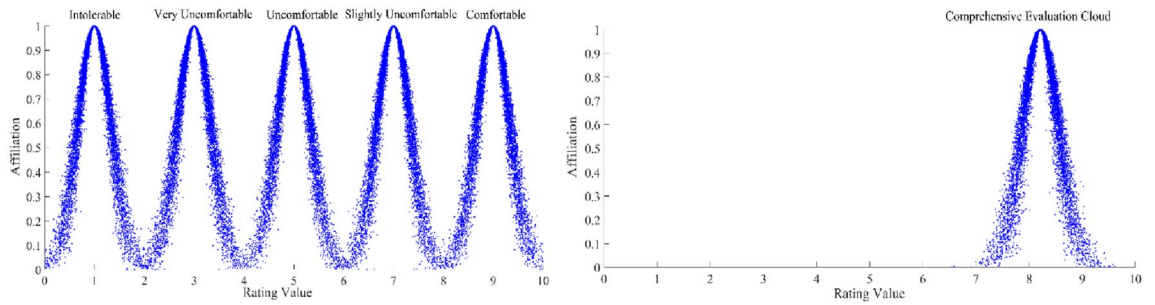


Figure 3. (a) Standard evaluation cloud; (b) Comprehensive evaluation cloud.

Standard evaluation cloud	Intolerable	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Comfortable
Similarity	0.000	0.000	0.000	0.0024	0.0757

Table 3. Similarity between integrated evaluation cloud and standard evaluation cloud.

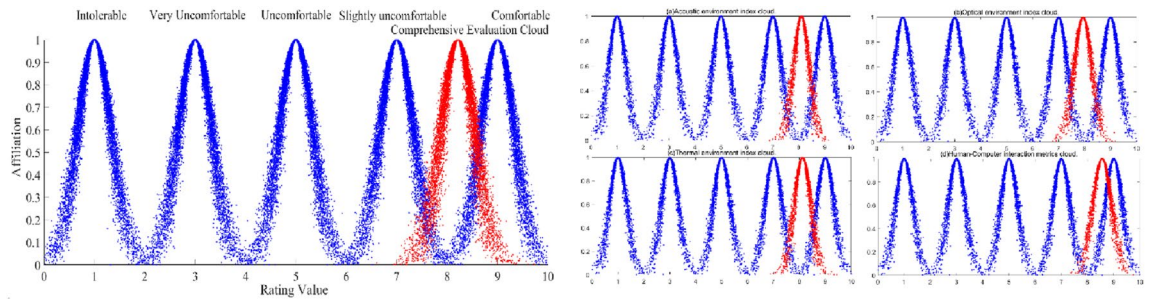


Figure 4. (a) Comparison of each indicator evaluation cloud with standard evaluation cloud. (b) Comparison between each indicator evaluation cloud and standard evaluation cloud.

Calculating the similarity. Subjective scales have been used for a long time for comfort evaluation^{47–50}. According to relevant standards and subjective evaluation scale specifications related to human engineering, combined with the actual situation of the automobile cockpit, the standard indoor environment comfort division, reference to the existing reference literature and consultation with experts, the evaluation criteria for the evaluation of the intelligent automobile cockpit comfort indicators are formulated^{51,52}. The criteria then are divided into "intolerable", "very uncomfortable", "uncomfortable", "slightly uncomfortable" and "comfortable", and the corresponding evaluation intervals are [0,2), [2,4), [4,6), [6,8), and [8, 10]; from unbearable to comfortable, the intelligent automobile cockpit comfort is improving. From equation $E_{xi} = \frac{d_{min_i} + d_{max_i}}{2}$ and $E_{ni} = \frac{d_{max_i} - d_{min_i}}{6}$, the intelligent automobile cockpit comfort evaluation standard cloud digital features can be obtained, as shown in Table 2; the standard evaluation cloud map is generated by the MATLAB forward cloud generator, as shown in Fig. 3a. Through the forward cloud generator and inverse cloud generator proposed by Chinese academician Li De-Yi in 1995⁴⁶, the comprehensive evaluation cloud map of the intelligent automobile cockpit comfort and the evaluation cloud of each index can be generated; the comprehensive evaluation cloud of the intelligent automobile cockpit comfort is shown in Fig. 3b.

The similarity between the comprehensive evaluation cloud and the standard cloud is calculated separately, and the evaluation level corresponding to the standard cloud with the greatest similarity is the final evaluation result. The similarity between the comprehensive evaluation cloud and the standard evaluation cloud was calculated as shown in Table 3.

Table 3 shows that the degree of comfort identified by the comprehensive evaluation cloud and the standard evaluation cloud rated as comfortable have the highest similarity, so the final evaluation result can be considered comfortable, but there is still some room for improvement. Meanwhile, through the MATLAB forward cloud generator, the cloud diagram was drawn by using the comprehensive evaluation cloud digital features and each standard evaluation cloud digital feature, and a similar comparison diagram was obtained, as shown in Fig. 4a. The cloud diagram can be more intuitively seen as consistent with the similarity calculation result. By drawing the similarity comparison diagram between each level of indicators and each standard cloud, it can be more intuitive to see the similarity between each level of indicators and each evaluation standard level for acoustic environment, optical environment, thermal environment and human–computer interaction, as shown in Fig. 4b.

	Intolerable	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Comfortable
Acoustic environment similarity	0.000	0.000	0.000	0.0026	0.0301
Optical environment similarity	0.000	0.000	0.000	0.0302	0.0094
Thermal environment similarity	0.000	0.000	0.000	0.0040	0.0378
Human–computer interaction similarity	0.000	0.000	0.000	0.0002	0.4819

Table 4. Similarity between each index evaluation cloud and standard evaluation cloud.

Results and discussion

In this paper, AHP is firstly used to determine the subjective weight of the comfort evaluation index of the intelligent automobile cockpit comfort. In the process of using the entropy weighting method to calculate the target weight, an improved algorithm is proposed. Compared with the traditional algorithm, it ensures that $\ln P_{ij}$ is mathematically meaningful, and controls the influence of the entropy value within a reasonable range, reducing artificial factors, and consider the actual situation of the evaluation indicators. Finally, the idea of game theory is introduced to determine this combination of weights. This approach fully considers that the subjective experience and objective inherent properties of the evaluation indices make the index weight replication more reasonable, which is conducive to the comprehensive evaluation of the intelligent automobile cockpit comfort. Among the four primary indicators affecting the intelligent automobile cockpit comfort, the human–computer interaction design has the greatest influence on the intelligent cockpit, followed by the thermal environment design, acoustic environment design and optical environment design.

In this paper, we use the intelligent automobile cockpit comfort evaluation model to evaluate the cockpit comfort of the Xiao-Peng P7 model automobile, and the four indicators are evaluated as comfortable in a comprehensive manner, as shown in Fig. 4a. From Table 4, we know that among the four first-level indicators, the acoustic environment, thermal environment and human–computer interaction environment can be considered comfortable, and only the optical environment design is considered slightly uncomfortable. This indicates that the intelligent cockpit design of the Xiao-Peng P7 intelligent automobile needs to focus on the influence of its optical environment aspects.

The intelligent cockpit comfort model based on game theory combination weights designed in this paper improves the intelligent automobile cockpit comfort impact evaluation system, which has certain reference value for future automobile engineers to design and manufacture intelligent cockpit. However, this paper has the following shortcomings in the work of evaluating the intelligent automotive cockpit comfort:

- (1) When calculating the objective weights of the acoustic environment, optical environment, thermal environment, and human–computer interaction using the improved entropy weight method in this paper, only five experts were invited to conduct the comfort level. The number of experts is small and has certain limitations. In the future, when further research work on the intelligent automotive cockpit comfort is carried out, the number of experts needs to be increased to make the evaluation of the intelligent automotive cockpit comfort more reasonable.
- (2) Due to the reason of the length, this paper only considers the influence of the primary indicators such as acoustic environment, optical environment, thermal environment, and human–computer interaction on the intelligent automotive cockpit comfort. In future research work, the automotive intelligent cockpit comfort will be further studied from the secondary indicators.

Data availability

All data generated or analyzed during this study are included in this published article.

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References

1. Lee, K. & Choi, J. Integrated vehicle safety control system for smart vehicles. *J. Auto J. Publ.* **34**(6), 20–25 (2012).
2. Kim, S. A study on the frequency allocation of WAVE for smart vehicle industry. *J. Inst. Electron. Inf. Eng.* **51**(6), 183–189 (2014).
3. Lee, S. H. & Kim, S. Y. An empirical study of the factors affecting adoption of a smart car—focused on twenties and thirties familiar with smart technology. *Reg. Ind. Stud.* **39**(2), 305–327 (2016).
4. Guo, Y. X. *et al.* Can driving condition prompt systems improve passenger comfort of intelligent vehicles? A driving simulator study. *Transport. Res. F Traffic Psychol. Behav.* **81**(11), 240–250 (2021).
5. Manogaran, G., Rodrigues, J. J., Kozlov, S. A. & Manokaran, K. Conditional support-vector-machine-based shared adaptive computing model for smart city traffic management. *IEEE Trans. Comput. Soc. Syst.* **9**(1), 174–183 (2021).
6. Gangadharan, K. V. & Chandramohan, S. Analytical studies on ride quality and ride comfort in chennai mass rapid transit system (MRTS) railroad vehicle. *J. Inst. Eng.* **99**(6), 732–742 (2017).
7. Wang, C., Zhao, X., Fu, R. & Li, Z. Research on the comfort of vehicle passengers considering the vehicle motion state and passenger physiological characteristics: Improving the passenger comfort of autonomous vehicles. *Int. J. Environ. Res. Public Health* **17**(18), 6821 (2020).

8. Zhou, Y. F. & Chen, S. R. Vehicle ride comfort analysis with whole-body vibration on long-span bridges subjected to crosswind. *J. Wind Eng. Ind. Aerodyn.* **155**, 126–140 (2016).
9. Sharma, R. C., Sharma, S., Sharma, S. K., Sharma, N. & Singh, G. Analysis of bio-dynamic model of seated human subject and optimization of the passenger ride comfort for three-wheel vehicle using random search technique. *Proc. Inst. Mech. Eng. Part K J. Multi-body Dyn.* **235**(1), 106–121 (2021).
10. Hemanth, K., Kumar, H. & Gangadharan, K. Vertical dynamic analysis of a quarter car suspension system with MR damper. *J. Braz. Soc. Mech. Sci. Eng.* **399**(1), 41–51 (2017).
11. Floyd, W. & Roberts, D. Anatomical and physiological principles in chair and table design. *Ergonomics* **2**(1), 1–16 (1958).
12. Caban, J., Maksym, P. & Zarajczyk, J. Acoustic comfort tests in the tractor cabin. *Proceedings of the 23rd International Scientific Conference on Transport Means* (2019).
13. Zvolenski, P., Ubomir, K., Volna, P. & Barta, D. Simulated computation of the acoustic energy transfer through the structure of porous media in application of passenger carriage body. *Proc. Eng.* **187**, 100–109 (2017).
14. Xue, J., Liu, W. & Liu, K. X. Influence of thermal environment on attendance and adaptive behaviors in outdoor spaces: A study in a cold-climate university campus. *Int. J. Environ. Res. Public Health* **18**(11), 6139 (2021).
15. Arvidsson, E., Nilsson, E., Bard-Hagberg, D. & Karlsson, O. J. Subjective experience of speech depending on the acoustic treatment in an ordinary room. *Int. J. Environ. Res. Public Health* **18**(23), 12274 (2021).
16. Nagare, R. *et al.* Access to daylight at home improves circadian alignment, sleep, and mental health in healthy adults: A crossover study. *Int. J. Environ. Res. Public Health* **18**(19), 9980 (2021).
17. Gharaveis, A., Yekita, H. & Shamloo, G. The perceptions of nurses about the behavioral needs for daylighting and view to the outside in inpatient facilities. *HERD Health Environ. Res. Des. J.* **13**(1), 191–205 (2020).
18. Gharaveis, A., Shepley, M. M. & Gaines, K. The role of daylighting in skilled nursing short-term rehabilitation facilities. *HERD Health Environ. Res. Des. J.* **9**(2), 105–118 (2016).
19. Vlk, F. *Dynamics of Engine Vehicles* (Czech Republic, 2003).
20. Ma, N. & Wang, Y. H. Complexity analysis method of human-machine interaction task in intelligent vehicle cockpit. *J. Graph.* **43**, 1–6 (2021).
21. Su, H. T. & Jia, Y. Y. Study of human comfort in autonomous vehicles using wearable sensors. *IEEE Trans. Intell. Transp. Syst.* **23**(8), 11490–11504 (2022).
22. Guo, T. M. *Research on Comprehensive Indoor Human Comfort and Evaluation Model* (Qingdao University of Technology, 2018).
23. Guo, Y. J. *Theory, method and application of comprehensive evaluation* 14–29 (Science Press, Bei Jing, 2007).
24. Wei, S. D. & Jiang, X. Q. A single-factor fuzzy evaluation method of using information entropy to determine the property weights. *Comput. Eng. Sci.* **32**(7), 93–95 (2010).
25. Liu, Y. X., Liu, S. & Wang, W. Y. Computation of weight in AHP and its application. *J. Shenyang Univ. Nat. Sci.* **26**, 372–375 (2014).
26. Tzeng, G. H. & Huang, J. J. *Multiple Attribute Decision Making: Methods and Applications* (CRC Press, 2011).
27. Zhang, X. Z. & Chen, G. Y. Integrated AHP with Delphi to decide the index weights in vendor evaluation. *Logist. Technol.* **9**, 71–74 (2005).
28. Cao, Q. K., Liu, K. Z. & Zhang, B. W. Calculation method of objective index weight by entropy. *J. Hebei Inst. Archit. Sci. Technol.* **17**(3), 40–42 (2000).
29. Jian-huo, Y. Expert score mechanism and optimal evaluation model. *Syst. Eng. Theory Pract.* **9**(2), 19–23 (1989).
30. Sun, Z. D., Xu, Z. S. & Da, Q. L. A. A model based on alternative similarity scale for uncertain multi-attribute decision-making. *Chin. J. Manag. Sci.* **9**(6), 58–62 (2001).
31. Ma, J., Fan, Z. P. & Huang, L. H. A subjective and objective integrated approach to determine attribute weights. *Eur. J. Oper. Res.* **112**(2), 397–404 (1999).
32. Park, J., Nam, C. & Kim, H. J. Exploring the key services and players in the smart car market. *Telecommun. Policy.* **43**(10), 101819 (2019).
33. Chen, X., Fang, Y., Chai, J. & Xu, Z. Does Intuitionistic Fuzzy Analytic Hierarchy Process Work Better Than Analytic Hierarchy Process? *Int. J. Fuzzy Syst.* **24**(2), 909–924 (2022).
34. Lee, S. Determination of priority weights under multiattribute decision-making situations: AHP versus fuzzy AHP. *J. Constr. Eng. Manag.* **141**(2), 05014015 (2015).
35. He, H. J., Tian, C., Jin, G. & An, L. An improved uncertainty measure theory based on game theory weighting. *Math. Probl. Eng.* **2019**, 1–8 (2019).
36. Chen, J. X. *et al.* Aircraft cockpit ergonomic layout evaluation based on uncertain linguistic multiattribute decision making. *Adv. Mech. Eng.* **6**, 698159 (2014).
37. Zhao, H. L., Yao, L. H., Mei, G., Liu, T. Y. & Ning, Y. S. A fuzzy comprehensive evaluation method based on AHP and entropy for a landslide susceptibility map. *Entropy* **19**(8), 396 (2017).
38. Dong, X., Lu, H., Xia, Y. P. & Xiong, Z. M. Decision-making model under risk assessment based on entropy. *Entropy* **18**(11), 404 (2016).
39. Liang, J. Y., Shi, Z. Z., Li, D. Y. & Wierman, M. J. Information entropy, rough entropy and knowledge granulation in incomplete information systems. *Int. J. Gen Syst* **35**(6), 641–654 (2006).
40. Wu, D. F., Wang, N. L., Yang, Z. P., Li, C. Z. & Yang, Y. P. Comprehensive evaluation of coal-fired power units using grey relational analysis and a hybrid entropy-based weighting method. *Entropy* **20**(4), 215 (2018).
41. Nash, J. Two-person cooperative games. *Econometrica J. Econom. Soc.* **21**, 128–140 (1953).
42. ANSI/ASHRAE Standard 55-2020. Thermal environmental conditions for human occupancy (2020).
43. DIS, I. Building environment design—indoor air quality—methods of expressing the quality of indoor air for human occupancy. (2005).
44. Ruan, C. *et al.* Construction risk assessment of urban wastewater deep-buried tunnels under-passing existing railway based on the improved entropy weight-unascertained measurement model. *Saf. Environ. Eng.* **28**(06), 84–90 (2021).
45. Tang, Z. C. & Shen, Y. M. An objective empowerment-based approach for assessing the importance of cyber assets. *Netw. Secur. Technol. Appl.* **2021**(04), 40–42 (2021).
46. Li, D. Y., Liu, C. Y. & Gan, W. Y. A new cognitive model: Cloud model. *Int. J. Intell. Syst.* **24**(3), 357–375 (2009).
47. Cooper, G. E. & Harper, R. J. *The use of pilot rating in the evaluation of aircraft handling qualities* (NASA, Washington, 1969).
48. Reid, G. B. & Nygren, T. E. The subjective workload assessment technique: A scaling procedure for measuring mental workload. *Adv. psychol.* **52**, 185–218 (1988).
49. Hart, S. G. & Staveland, L. E. Development of nasa-tlx (task load index): Results of empirical and theoretical research. *Adv. psychol.* **52**(6), 139–183 (1988).
50. Shackel, B., Chidsey, K. D. & Shipley, P. The assessment of chair comfort. *Ergonomics*. **12**(2), 269–306 (1969).
51. Annett, J. Subjective rating scales in ergonomics: A reply. *Ergonomics*. **45**(14), 1042–1046 (2002).
52. Annett, J. Subjective rating scales: Science or art?. *Ergonomics*. **45**(14), 966–987 (2002).

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Author contributions

J.Y. conceived and designed the study. S.X. proposed the method and contributed to the analysis. R.Q. and Y.C. made an investigation. J.Y. accumulated resources. J.Y., S.X., C.H. and D.D. wrote the original draft. J.Y., C.H. and D.D. contributed to the review and editing. All authors gave their final approval of the manuscript version to be submitted.

Competing interests

The authors declare no competing interests.

Additional information

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