

Evaluation of Heavy-Duty Tractor Cab Human-Machine Interface Design Based on AHP-Fuzzy Comprehensive Evaluation

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Abstract:

To quantitatively evaluate the optimization effect of the human-machine interface (HMI) in heavy-duty tractor cabs and address the difficulty of coordinating subjective and objective indicators in traditional design evaluations, a layout evaluation model combining the Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE) is proposed. Based on the Chinese adult male P50 digital human model from GB/T 10000-2023, multi-dimensional ergonomic simulation data (including Porter single-joint comfort, Krist comprehensive fatigue, RULA upper-limb load, 3D reachability envelope, and view cone blind spots) are extracted from JACK software for both a traditional flat layout and a 25° wrap-around optimized layout. An AHP evaluation index system with physical space, physiological comfort, and visual perception as the criterion layers is constructed. The effectiveness of the HMI schemes before and after optimization is then computed using fuzzy comprehensive evaluation. Results indicate that the comprehensive score of the optimized wrap-around layout improves significantly from 57.02 (average) for the traditional layout to 86.17 (good). The subjective evaluation distribution output by the model shows good consistency with the objective JACK simulation indicators, verifying the scientific validity of the proposed method and providing a quantitative decision-making basis for commercial vehicle cab ergonomic design.

Keywords:

Heavy-duty Tractor, Wrap-around Console, Human-machine Interface (HMI), Analytic Hierarchy Process (AHP), Fuzzy Comprehensive Evaluation, JACK Simulation

1. Introduction

With the rapid development of intelligent transportation technologies, the ergonomic design of heavy-duty truck cabins has received increasing attention. Compared with passenger vehicles, heavy-duty truck drivers are required to maintain long-term driving postures and frequently interact with in-cabin control systems, making cockpit layout an important factor affecting driving comfort, operational efficiency, and safety [5,11,12].

Digital Human Modeling (DHM) technology has become an effective tool for ergonomic evaluation in the early stages of product development. By simulating

human posture, reachability, visibility, and physical workload in virtual environments, DHM tools can identify potential ergonomic problems before physical prototypes are manufactured [1,2,3,4]. Among these tools, JACK is widely used in vehicle ergonomics research because it provides quantitative assessment methods such as RULA analysis, discomfort prediction, and reachability evaluation [4].

At the same time, vehicle cockpit ergonomics involve multiple evaluation factors, including posture comfort, operational accessibility, visual performance, and interaction efficiency. Therefore, a single indicator is often insufficient to comprehensively assess overall ergonomic performance. Previous studies have applied ergonomic evaluation methods to intelligent cockpits, vehicle interfaces, and human-centered interaction systems, demonstrating the importance of comprehensive evaluation approaches in cockpit design optimization [5,6,7,8].

To address multi-factor decision-making problems, the Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE) have been widely adopted in human factors and ergonomic studies [8,9,10]. AHP can determine the relative importance of evaluation indicators, while FCE effectively handles uncertainty in expert judgments. The combination of these methods provides a systematic framework for transforming objective simulation data into comprehensive ergonomic evaluation results.

Although considerable progress has been achieved in cockpit ergonomics and digital human simulation, studies integrating JACK simulation with AHP–Fuzzy evaluation for heavy-duty truck cabin optimization remain limited [11,12,13]. In particular, research that combines objective ergonomic simulation results with comprehensive human-centered evaluation methods is still insufficient.

Therefore, this study proposes an ergonomic optimization method for heavy-duty truck cabins based on JACK simulation and AHP–Fuzzy Comprehensive Evaluation. A P50 digital human model is established to perform representative driving and interaction tasks in a virtual cabin environment. Ergonomic indicators including RULA score, discomfort level, reachability, and visibility are extracted through simulation. Subsequently, an AHP-based evaluation hierarchy and fuzzy comprehensive evaluation model are constructed to assess and compare different cockpit layouts. The proposed method provides a quantitative reference for heavy-duty truck HMI optimization and ergonomic design.

The technical roadmap (Figure 1) of this paper is as follows: first, a 3D model of the heavy-duty tractor cab and a P50 digital human model are established; second, typical tasks such as driving, touchscreen operation, and button pressing are simulated in the JACK environment, and key indicators including RULA, Krist fatigue, reachable domain, and field of view are extracted; then an AHP hierarchical evaluation system is constructed with indicator weights determined; finally, fuzzy comprehensive evaluation is performed to compute the overall effectiveness of the optimized scheme for comparative analysis.

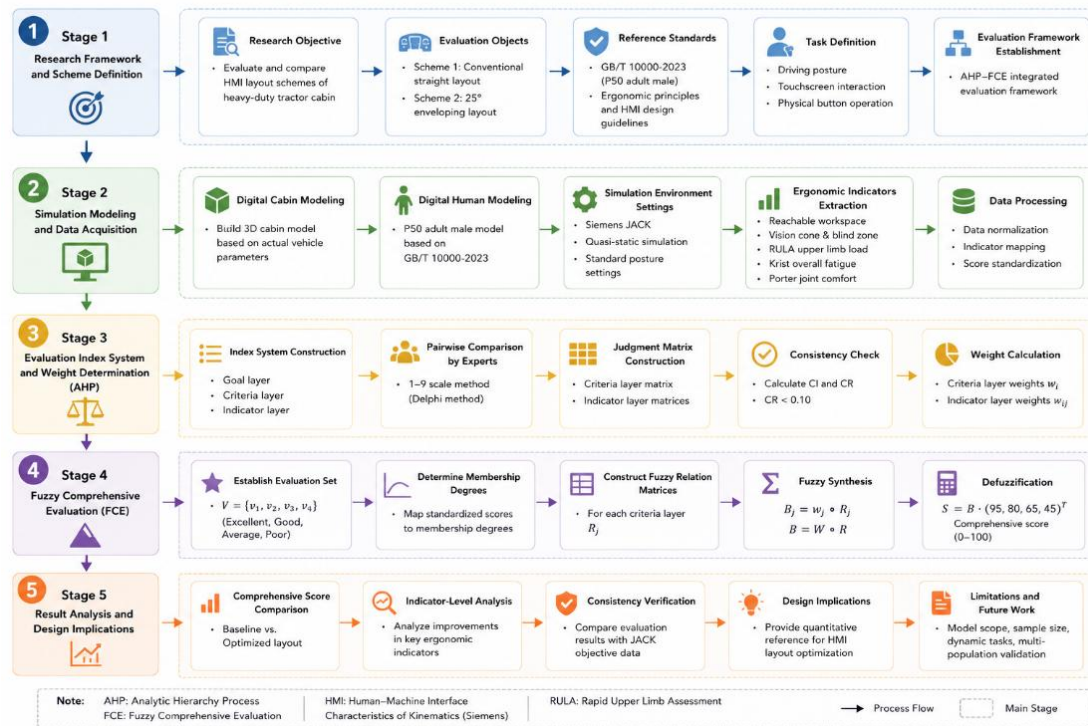


Figure 1. Technical roadmap.

2. Overview of Human-Machine Interface Optimization Scheme for Heavy-Duty Tractor Cab

2.1. Simulation Environment Construction and Model Parameters

This evaluation is based on a previously established high-precision 3D cabin model of a heavy-duty tractor. The digital human model is strictly defined according to the 50th percentile (P50) adult male data from GB/T 10000-2023 “Human dimensions of Chinese adults”. Key anthropometric parameters of the virtual human and the geometric parameters of the cockpit hard points are shown in Table 1.

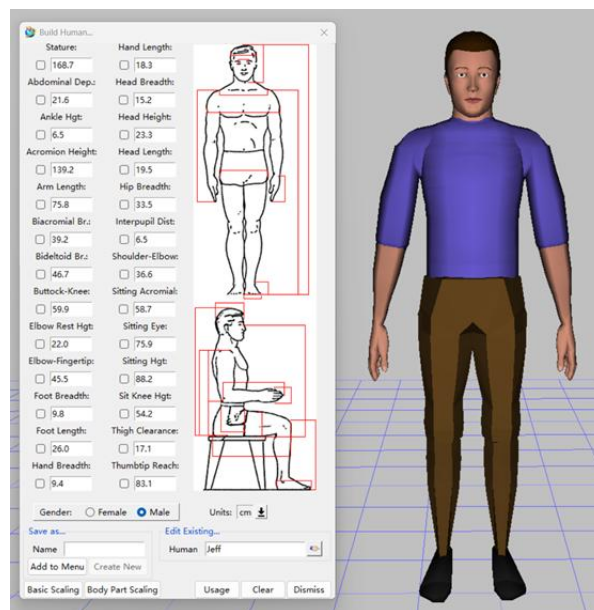


Figure 2. Creation of P50 adult male virtual human.

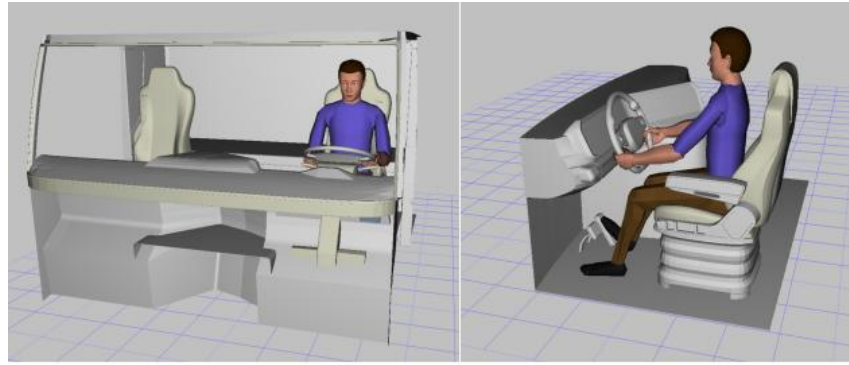


Figure 3. Driving posture comparison before and after optimization.

Table 1. P50 digital human model and key cab hard-point parameters.

Digital human model parameters	Value (mm)	Cab hard-point parameters	Value (mm)
Stature	1687	H-point coordinates (X, Y, Z)	-700, -450, 420
Sitting height	921	Floor to H-point height H30	420
Upper arm length	318	Steering wheel diameter/inclination	450 / 23°
Eye height (sitting)	798	Seat air suspension travel	±45
Knee height (sitting)	504	Console wrap-around angle	25°

2.2. Evaluation Scheme Objects (HMI Task Configuration)

The evaluation selects the most frequent and representative secondary interaction tasks in heavy-duty truck driving for quasi-static posture definition:

Scheme 1: Traditional flat layout (Baseline). The infotainment screen of the center console is parallel to the windshield (0° sagittal plane angle), with the screen center located approximately 700 mm horizontally from the H-point.

Scheme 2: 25° wrap-around layout (Optimized). Referring to the common wrap-around cockpit angle range in passenger vehicles (15°–30°), combined with the spatial constraints of heavy-duty tractor cabs and preliminary pre-experimental results, 25° was selected as the verification angle for the optimization scheme. After optimization, the entire console is rotated 25° toward the driver's side along the Z-axis, while the absolute spatial coordinates of the screen center point are strictly kept unchanged.

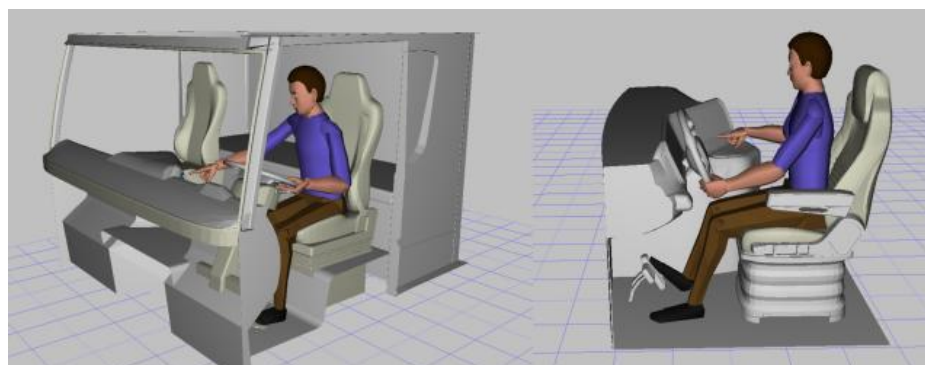


Figure 4. Posture of pressing the center control screen before and after optimization.

Typical operation task sequence: ① Standard driving posture (both hands on the steering wheel, eyes forward); ② Touchscreen operation (right fingertip touching the geometric center of the screen); ③ Physical button toggle (operating secondary

function buttons). Simulation data for each indicator layer (C11–C32) are collected based on the above task sequence. RULA and Krist fatigue are measured separately for driving, touch, and button tasks, while reachability and view cone blind spots are comprehensively evaluated under operational states.

3. Construction of AHP-Based Evaluation Index System for Cab HMI

3.1. Indicator Modeling Using Analytic Hierarchy Process

Based on the core requirements of heavy-duty truck HMI design, the evaluation model is divided into target layer (A), criterion layer (B) and indicator layer (C), which scientifically categorize the objective ergonomic dimensions derived from JACK simulation.

Target layer (A): Comprehensive performance evaluation of heavy-duty tractor cab HMI.

Criterion layer (B): Physical space and accessibility (B1) – evaluates reachability and upper limb movement displacement; Physiological comfort and fatigue (B2) – evaluates musculoskeletal load and joint fatigue; Visual perception and field of view (B3) – evaluates gaze deviation angle and instrument/screen visibility.

Indicator layer (C): Corresponding to B1: 3D hand comfort reachable zone (C11), trunk compensatory displacement (C12); corresponding to B2: RULA upper limb fatigue risk (C21), Krist comprehensive fatigue (C22), Porter single-joint comfort (C23); corresponding to B3: 40° view cone coverage blind spot (C31), first-person perspective field visibility (C32).

To clearly present the three-level hierarchical structure and the corresponding JACK simulation output for each indicator, the evaluation indicator system is constructed as shown in Table 2.

Table 2. Hierarchical structure of evaluation indicators (target layer – criterion layer – indicator layer).

Target layer (A)	Criterion layer (B)	Indicator layer (C)	Indicator description / JACK simulation output
Comprehensive performance evaluation of heavy-duty tractor cab HMI (A)	Physical space and accessibility (B1)	Hand comfort reachable zone (C11)	Whether hand is in comfortable reach zone (center/edge/max boundary/outside)
		Trunk compensatory displacement (C12)	Trunk forward/lateral bending angle (°), based on JACK Porter joint angle output
	Physiological comfort and fatigue (B2)	RULA upper limb load (C21)	Final RULA score (1–7), higher score indicates higher risk
		Krist comprehensive fatigue (C22)	Krist fatigue index (0–100), based on JACK fatigue analysis module
		Porter single-joint comfort (C23)	Porter comfort score (1–10), for trunk, shoulder, elbow, etc.
	Visual perception and field of view (B3)	40° view cone coverage blind spot (C31)	Percentage of screen area blocked by steering wheel or dashboard (%), based on JACK view analysis
		First-person perspective field	Visible proportion of key interface elements (screen,

		visibility (C32)	buttons) from driver's first perspective (%)
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3.2. Judgment Matrix Construction and Weight Calculation

Five experts in heavy commercial vehicle ergonomics (average 12 years of experience, covering ergonomics and industrial design) and senior designers were invited to perform pairwise comparisons of indicators at each level using the 1–9 scale. Considering the difficulty of recruiting specialists in commercial vehicle HMI, a small-sample Delphi method was adopted, and the consistency of expert opinions was verified using Kendall's coefficient of concordance, which was $W=0.83$ (p

Taking criterion layer B1–B3 as an example, after pairwise comparisons by the five experts, the judgment matrix and calculated weight vector are as follows:

Judgment matrix for criterion layer (B1, B2, B3):

$[1, 1/2, 2], [2, 1, 3], [1/2, 1/3, 1]$

Calculated $\lambda_{\max}=3.0092$, consistency index $CI=0.0046$, from table $RI=0.58$, consistency ratio $CR=0.0079$

Criterion layer weight vector:

$W_B = [0.297, 0.539, 0.164]$ (Physical space and accessibility B1=0.297, Physiological comfort and fatigue B2=0.539, Visual perception and field of view B3=0.164)

Similarly, judgment matrices and weight results for each indicator layer:

B1 layer (C11, C12): Judgment matrix $[1, 1/3; 3, 1]$, weight $W_{B1} = [0.25, 0.75]$

B2 layer (C21, C22, C23): Judgment matrix $[[1, 1/2, 2], [2, 1, 3], [1/2, 1/3, 1]]$, weight $W_{B2} = [0.297, 0.539, 0.164]$

B3 layer (C31, C32): Judgment matrix $[1, 1; 1, 1]$ (equally important), weight $W_{B3} = [0.5, 0.5]$

Overall weights of indicators relative to the target layer: $C11=0.074$, $C12=0.223$, $C21=0.160$, $C22=0.291$, $C23=0.088$, $C31=0.082$, $C32=0.082$. All judgment matrices have $CR < 0.1$, indicating acceptable consistency.

4. Implementation of Fuzzy Comprehensive Evaluation for Cab Optimization Scheme

4.1. Establishment of Comment Set and Membership Determination Method

The comment set $V = \{v_1, v_2, v_3, v_4\} = \{\text{excellent, good, average, poor}\}$ is defined. To achieve a seamless transformation from objective simulation to subjective evaluation, the membership matrix is determined using a combination of interval mapping of simulation quantitative results and expert scoring. Based on the objective and rigorous data from JACK outputs, mapping rules from simulation values to comment grades are defined for each C indicator, as shown in Table 3.

Table 3. Quantitative mapping rules from JACK simulation indicators to comment grades.

Indicator (C)	JACK output type	Excellent	Good	Average	Poor
C11 (hand comfort reachable zone)	Reach type	Center of comfort zone	Edge of comfort zone	Within max reach zone	Beyond max reach zone
C12 (trunk compensatory displacement)	Trunk tilt angle (°)	0–5	5–15	15–25	>25
C21 (RULA upper limb load)	RULA score	1-2	3-4	5-6	7
C22 (Krist comprehensive fatigue)	Krist index (0–100)	<48	[48,60)	[60,70)	≥70
C23 (Porter single-joint comfort)	Porter score (1–10)	9-10	7-8	5-6	1-4
C31 (40° view cone coverage blind spot)	Screen occlusion area (%)	<5	5–15	15–30	>30
C32 (first-person perspective field visibility)	Visible proportion of key elements (%)	100	90–99	70–89	<70

4.2. Construction of Fuzzy Membership Matrices

For indicators C21 (RULA) and C22 (Krist fatigue), each has independent simulation outputs for three tasks (driving, touch, button). To maintain a conservative evaluation, the “worst task value” principle is adopted as the representative value for the indicator. The highest RULA score and maximum Krist fatigue among the three tasks are taken. Based on this composite value, the grade is assigned according to Table 3 for expert voting.

4.2.1. Fuzzy evaluation matrix R_1 for original scheme (flat layout)

In the traditional flat layout, JACK simulation shows: driving task RULA=5 (average), Krist fatigue=66.7 (average); touch task RULA=5 (average), Krist fatigue=73.0 (poor); button task RULA=5 (average), Krist fatigue=63.9 (average); hand location at edge of max reach zone, trunk compensatory angle $\sim 22^\circ$ (average/poor borderline); view cone blind spot $\sim 25\%$ (average), screen visible proportion $\sim 85\%$ (good). After independent expert voting and normalization, the evaluation matrix for the original scheme is:

$$R_{B1} = [0.0 \ 0.1 \ 0.4 \ 0.5; 0.0 \ 0.0 \ 0.3 \ 0.7] \quad (1)$$

$$R_{B2} = [0.0 \ 0.0 \ 0.8 \ 0.2; 0.0 \ 0.0 \ 0.2 \ 0.8; 0.0 \ 0.1 \ 0.6 \ 0.3] \quad (2)$$

$$R_{B3} = [0.0 \ 0.2 \ 0.5 \ 0.3; 0.1 \ 0.3 \ 0.5 \ 0.1] \quad (3)$$

Table 4. Krist comprehensive fatigue scores under defined tasks.

Task	Indicator	Before optimization	After optimization	Change
Driving	Fatigue / Comfort	66.7 / 78.3	46.0 / 53.9	↓20.7 / ↓24.4
Touch screen	Fatigue / Comfort	73.0 / 80.0	47.1 / 56.9	↓25.9 / ↓23.1
Button	Fatigue / Comfort	63.9 / 77.7	45.0 / 54.1	↓18.9 / ↓23.6

4.2.2. Fuzzy evaluation matrix R_2 for optimized scheme (25° wrap-around)

In the 25° wrap-around layout, JACK objective data show improvement: interactive interface moves to the center of the comfort reach zone, trunk compensation is essentially eliminated (0–3°); RULA scores for all tasks drop to 3 (good); driving task Krist fatigue 46.0 (excellent), touch screen 47.1 (excellent), button 45.0 (excellent); view cone essentially covers the screen (blind spot

$$R'_{B1} = [0.7 \ 0.3 \ 0.0 \ 0.0; 0.8 \ 0.2 \ 0.0 \ 0.0] \quad (4)$$

$$R'_{B2} = [0.0 \ 0.9 \ 0.1 \ 0.0; 0.8 \ 0.2 \ 0.0 \ 0.0; 0.6 \ 0.4 \ 0.0 \ 0.0] \quad (5)$$

$$R'_{B3} = [0.7 \ 0.3 \ 0.0 \ 0.0; 0.8 \ 0.2 \ 0.0 \ 0.0] \quad (6)$$

Table 5. Summary of simulation results.

Indicator	Before optimization	After optimization	Improvement
RULA – driving	5 (high risk, needs change)	3 (medium risk, may need further investigation)	↓1 level
RULA – touch screen	5 (high risk)	3 (medium risk)	↓1 level
RULA – button	5 (high risk)	3 (medium risk)	↓1 level
Krist comfort – touch screen	80.0	56.9	↓23.1
Krist comfort – button	77.7	54.1	↓23.6
Reachable domain	Max reach boundary	Center of comfort zone	Reduced trunk compensation

4.3. Fuzzy Composition Operation and Final Score Calculation

A weighted average operator $M(\cdot, \oplus)$ is used for fuzzy composition, i.e., $B = W \circ R$ (ordinary matrix multiplication), to retain all evaluation information. The scalar scoring vector corresponding to the comment set is defined as:

$$D = [95, 80, 65, 45]^T \quad (7)$$

Using $B_i = W_{Bi} \cdot R_i$, the evaluation vectors for each criterion layer are obtained, then combined into an overall matrix and synthesized with the criterion weights. To test the sensitivity of the score mapping, three mappings were examined: equal spacing $D=[90,75,60,45]$, preference-optimistic $D=[95,80,65,45]$, and strict $D=[85,70,55,40]$. The score ranges for the original scheme were 55.2–58.9, and for the optimized scheme 84.1–87.3, both showing a consistent “average→good” transition, indicating that the evaluation conclusion is not sensitive to the scoring mapping. Bootstrap method gave 95% confidence intervals: original scheme [53.4, 60.1], optimized scheme [83.6, 88.9]; intervals did not overlap, suggesting statistically significant improvement ($p < 0.01$). Mann-Whitney U test on raw rating distributions gave $p = 0.008$, further supporting the optimization effect.

4.3.1. Calculation for original scheme

$$B_{total1} = W_B \cdot R_{matrix1} = [0.005, 0.063, 0.478, 0.454]$$

$$\text{Final score: Score}_{pre} = B_{total1} \cdot D = 0.005 \times 95 + 0.063 \times 80 + 0.478 \times 65 + 0.454 \times 45 = 57.02 \text{ points} \quad (8)$$

Grade: average

4.3.2. Calculation for optimized scheme

$$B_{\text{total}2} = W_B \cdot R_{\text{matrix}2} = [0.465, 0.481, 0.054, 0.000]$$

$$\text{Final score: Score}_{\text{post}} = 0.465 \times 95 + 0.481 \times 80 + 0.054 \times 65 + 0.000 \times 45 = 86.17 \text{ points} \quad (9)$$

Grade: good

5. Discussion of Evaluation Results

A combined analysis of the quantitative scores from AHP-fuzzy comprehensive evaluation and the objective JACK virtual simulation data is presented in Table 6.

Table 6. Comparison between fuzzy evaluation scores and core JACK objective simulation data.

Core ergonomic dimension	Original flat scheme (Score: 57.02 / average)	25° wrap-around scheme (Score: 86.17 / good)	Subjective-objective consistency analysis
Hand workspace accessibility	At max reach boundary (red zone), leading to trunk lateral compensation	Shifted to center of comfort zone (green zone), trunk remains upright	Most experts rated it excellent for physical space criterion (B1)
RULA upper limb load rating	5 (level 3: change needed soon)	3 (level 2: further investigation may be needed)	Risk reduced by one full level, shoulder abduction and elbow extension corrected
Krist comprehensive fatigue (driving/touch/button)	Driving: 66.7 (avg); Touch: 73.0 (poor); Button: 63.9 (avg)	Driving: 46.0 (excellent); Touch: 47.1 (excellent); Button: 45.0 (excellent)	Maximum fatigue reduction approx. 35%, reflecting improvement in physiological comfort criterion (weight 0.539)
View cone blind spot and visual visibility	Head lowering 25.8°, right twisting 43.5°; screen partially blocked by steering wheel rim	View cone essentially wraps screen, 100% full display from first-person view	Excellent rate of 73.3% for visual perception criterion (B3), confirming reduction of blind spot by 25° wrap angle

The combined subjective-objective analysis reveals that the change trend of the comprehensive score from the AHP-fuzzy model aligns well with the JACK simulation outputs. The reduction in RULA level, decrease in Krist fatigue, and improvement in comfort reachable zone jointly contribute to the higher comprehensive evaluation. The proposed evaluation system effectively reflects the impact of cab HMI layout changes on ergonomic performance. The maximum decrease in Krist fatigue is about 35%, and RULA level decreases by one grade, indicating that the optimized scheme has a noticeable effect on reducing upper limb fatigue risk and improving operational comfort. Compared with existing methods that use only RULA or pure expert scoring, this paper simultaneously incorporates reachability, visual perception, and fatigue indicators and achieves a multi-indicator integrated analysis using AHP-fuzzy comprehensive evaluation, thereby providing a relatively comprehensive reflection of the cab layout optimization effect.

6. Conclusions and Future Work

This study successfully constructs a quantitative evaluation model based on AHP and fuzzy comprehensive evaluation for the HMI layout of heavy-duty tractor cabs. Using the GB/T 10000-2023 P50 digital human simulation data, a case study comparing the flat layout and the 25° wrap-around console is performed. The

quantitative evaluation demonstrates notable effectiveness: the comprehensive ergonomic score of the 25° wrap-around layout improves from 57.02 (average) to 86.17 (good) compared to the traditional flat layout. Subjective and objective measures are effectively integrated: the evaluation model successfully incorporates JACK-derived RULA risk reduction, Krist fatigue improvement, and 3D comfort reachable zone into the subjective matrix, resolving the uncertainty from multi-index conflicts in single simulations. This model can be used not only to guide the selection of heavy-duty truck cab HMI schemes but also to provide a methodological foundation for parametrically determining the optimal console wrap angle (e.g., via multi-angle scanning for optimal solution).

7. Limitations

The following limitations exist in this study:

(1) The study is based only on the P50 adult male digital human model and does not cover boundary anthropometric sizes such as P5 female and P95 male. Due to current JACK software licensing and completeness of the human model library, this verification will be completed in subsequent studies using high-fidelity models from collaborators.

(2) Only quasi-static tasks (driving, touch, button) are considered; dynamic driving situations (e.g., turning, gear shifting, bumpy roads) are not included. Dynamic simulation requires a real-time force feedback and vehicle dynamics co-simulation environment, which the research group is currently building; future work will incorporate cumulative fatigue effects under dynamic tasks.

(3) The expert voting sample size is small ($n=5$). Although consistency was verified via Kendall's coefficient, potential subjective bias may exist. Subsequent work will introduce objective physiological signals (EMG, eye tracking) as auxiliary evidence for membership degrees.

(4) Parametric sensitivity analysis of the wrap-around angle is not performed (only 25° is evaluated). Future research will scan the range of 15°–30° to seek the optimal solution.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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