Assignment of Weights to Indexes in Evaluating Usability of Child Safety Chairs Based on AEMV Synthetic Weighting Method

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Abstract. Usability is a decisive factor of any child safety restraint (child-safety chair) in assessing its functions, making purchase decision, and using it properly and effectively. The article takes advantage of well-developed child chair evaluation regulations and processes worldwide, itemizes and discusses every correlation between usability evaluation index and misuse, and thus formulates usability evaluation indexes system consisting of symbol usability, usability of user manual, usability of child protection and usability of chair installation; builds AEMV synthetic weight assignment modeling combining AHP method, Entropy method and Mean Variance method, on account of usability evaluation that can be subjectively biased, and index weighting that can not be decided properly, in consideration of expertise and objective test data; and calculates any index weight assigned to child chair usability evaluation based on the present synthetic weight assignment modeling, and justifies the scientific strength and objectivity of the weights assignment method in question by means of result comparison and analysis.

1. Introduction
Thanks to increasing numbers of purchased vehicles and enhanced awareness of consumers about safety, child-safety restraint systems have drawn greater attention than ever. In developed nations, child safety restraint systems are legally compulsory and as a result widely applied. The systems are equipped on about 90% of vehicles in the US, Canada, Australia and Germany equip with the system [1-4]. In contrast to this situation, laws and regulations on compulsory use of child safety chairs for child occupants are only locally constituted in Shanghai, Shenzhen and Shandong. The legislation is poorly implemented due to limited enforcement. In 2015, a survey conducted by the AQSIQ Defective Product Administrative Center showed that of the 4,900 parent who replied inquiries in Beijing, Shanghai, Guangzhou, Jinan and Chongqing, 60.2% have his/her child/children travel in car every week, while simply 19.7% use child safety restraint systems. It can be a huge gap. According to statistics, correct use of child safety chairs reduces fatal injuries of children in traffic accidents by 71%, and serious injuries by 67%[5]. On the contrary, unqualified child safety chairs or misuse will result in greater fatal risk, rather than expected protection [6]. Certain measures are adopted worldwide to ensure effective protection by child safety chairs. Continuous improvement and modifications of technical regulations and standards for child safety restraint systems on the one hand motivate manufacturers to enhance constantly product quality by means of product certification and callback campaigns[7]; and performance evaluation and misuse studies on child safety restraint systems on the other hand are implemented to practically guide consumers to correctly select and use child safety chairs[8-9]. GB27887-2011 Restraining devices for child occupants of power-driven vehicles came
into effect as of 1st July 2012. On 22nd January 2014, the AQISQ put child-safety chairs on China Compulsory Certification list. According to survey data released in 2013 by China Automotive Technology & Research Center CATARC, child safety chairs made in China satisfy international standards in terms of technical design, manufacturing processes and quality. Products are most exports. Therefore, performance evaluation and possible callback campaigns of child safety chairs would be major concerns in child occupants’ protection in China.

A study project team was organized in 2011 and occupied in study on usability evaluation system of child-safety chair in response to market features and status quo of child-safety chair products in China. Members of the joint team came from the AQSIQ Defective Product Administrative Center, Tsinghua University, National Center of Supervision and Inspection on Motor Vehicle Products Quality (Shanghai). In May 2014, the Usability Evaluation Regulations and Processes of Child Safety Chair in China were published as periodical study outcome. Usability evaluation of child safety chair serves rational consumption and prevents misuse of child safety chairs, so as to ensure on-board safety of child occupants; it works also as a set of guidelines for manufacturers in designing and producing products, which also help improve usability with better built child safety chair products. Weights assigned to evaluation indexes have major impact on evaluation results. Usability evaluation indexes are most qualitative, the present regulations and processes adopt Analysis Hierarchy Process (AHP) for assignment. AHP depends on expert experience and can be subjective. Its results could become less precise somewhat [10]. Instead of single weighting method with poor outcomes, various synthetic weighting methods are getting popular. For instance, literature [11-12] combine AHP and Entropy methods to decide weights to be assigned to evaluation indexes; literature [13] combine AHP and CPA methods to decide weights to be assigned to synthetic indexes for evaluating operation of storage tank zone; literature [14] combine Entropy method, Max Dispersion method and Inter-Class Standard Variance method and CRITIC method to decide weights to be assigned to categorical features of stored-grain insects based on extension theory. Synthetic weighting method is an amalgamation of expertise and objective test data. The present article integrates AHP, Entropy and Mean Variance methods together into original AEMV synthetic weight assignment modeling for index weighting of usability evaluation of child-safety chairs. It is an approach with more scientifically objective results than AHP alone.

2. Usability Evaluation Index System of Child Safety Chair
There are globally 2 types of regulations for performance evaluation of child-safety chairs: synthetic evaluation regulations, including dynamic performance evaluation and usability; and usability evaluation regulations. Usability is a concept derived by Jakob Nielsen. It indicates if a product is performance friendly [15]. A child-safety chair is well protective as long as its safety performance is logically designed and manufactured as well as it is correctly and properly used. Usability of any child-safety chair therefore shall be equally composed of operation-friendly or comfort-oriented equipment, and easy and smart design to keep it from misuse.

The article takes advantage of international studies on chair chair evaluation systems, especially US research results, itemizes and analyses correlation between usability evaluation index and misuse, and thus formulates a usability evaluation index system in response to market situation and status quo of child-safety chair products in China. Refer to Figure 1 for details. The system consists of 4 indexes, i.e. symbol usability, usability of user manual, usability of child protection and usability of chair installation. Symbol usability refers to completeness, preciseness and legibility of any information delivered by a symbol; usability of user manual refers to completeness, preciseness and legibility of any information delivered by a user manual; usability of child protection refers to ensured safety and easy operation when a child is fixed to a child-safety chair; and usability of chair installation refers to ensured safety and easy operation when a child-safety chair is fixed to vehicle seat.
3. AEMV Synthetic Weight Assignment Modeling

As for an index-based evaluation, weights that indicate respectively significance shall be assigned to fit indexes. A weight decides the contribution of every assigned index. Determination of each weight lays consequently the ground for evaluation. AHP, developed by American operation-focused primary theorician Saaty, is an understandable weighting method widely adopted in various fields[16]. Basically, it decomposes complex problems into sub-problems and elements at hierarchies. Indexes are compared to each other two at a time by professional hands with respect to their impact on any element relevant to decision making. A matrix of judgement is then structured. Maximum eigenvalue and associated eigenvector of the matrix are calculated, so as to decide a weight of any factor with certain significance. AHP method comes with risks when making decisions due to uncertain experience and subjectivity of an operator. Dispersion of evaluation data is introduced here as countermeasure to decide respective weight, wider the scatter of any data, greater the weights assigned[17]. Entropy measures uncertainty. Less an uncertainty, less an entropy value[18]. Mean variance is also possible for measuring data scatter degrees. Greater standard deviation means greater significance an index value has in synthetic evaluation, and therefore greater weight. In consideration of expertise and evaluation data at the same time, AHP method, Entropy method and Mean Variance method are applied jointly. AEMV synthetic weight assignment modeling is thus formulated:

\[
\begin{pmatrix}
  w_1 \\
  w_2 \\
  \vdots \\
  w_n
\end{pmatrix} = \begin{pmatrix}
  I_1 & A & E + Mv \\
  I_2 & A & E + Mv \\
  \vdots & A & E + Mv \\
  I_n & A & E + Mv
\end{pmatrix} \cdot R
\]

Of the coefficients, \([I_1 \ I_2 \ \cdots \ I_n]\) is \(n\) as many as \(N\) indexes; \(A\) is AHP method; \(E\) is Entropy method; \(Mv\) is Mean Variance method; \(R\) is correlation among the present 3 weighting methods; \([w_1 \ w_2 \ \cdots \ w_n]\) is weight values gained jointly thanks to the 3 weighting methods.

Given \(W_S\) is the weight vector based on AHP method, \(W_{O1}\) is the weight vector based on Entropy method, and \(W_{O2}\) is the weight vector based on Mean Variance method. \(W_{O1}\) and \(W_{O2}\) are gained based on evaluation index measurements and have geometric mean values: \(W_O = \left( \prod_{i=1}^{p} W_{Oi} \right) ^{1/p}\)
\[ \pi_{1,2,1} \Rightarrow \]

\[ \sum_{i=1}^{p} \pi_{i} = 1, 2, \ldots, p \Rightarrow \]

\[ W_{O} \] can be normalized: \[ W_{O} = \left[ w_{O_{i}} = \frac{w_{O_{i}}}{\sum_{i=1}^{p} w_{O_{i}}} \right] i = 1, 2, \ldots, p \Rightarrow \]

have \[ W_{S} \] and \[ W_{O} \]

integrated by means of additive ensemble method: \[ W = \alpha W_{S} + \beta W_{O} \]; wherein \( \alpha \) and \( \beta \) are both undetermined coefficients for synthesis, and \( \alpha > 0, \beta > 0, \alpha + \beta = 1 \), and values can be calculated via coefficient variation method: \( \alpha = \frac{n}{n-1} T_{S} \); and \( \beta = 1 - \alpha \); wherein \( T_{S} \) serves as variation coefficient of individual weight of set \( W_{S} \), \( T_{S} = \frac{2}{n} \left( P_{1} + P_{2} + \cdots + P_{n} \right) \) \( \frac{n+1}{n} \); and \( P_{1}, P_{2}, \ldots, P_{n} \) indicate sequencing of \( W_{O} \) vectors from lesser values to greater values.

4. Verification by Application

Provided the usability evaluation index system of child-safety chairs in Figure 1, \( M_{1}, M_{2}, M_{3}, M_{4} \) indicate 4 indexes respectively as symbol usability, usability of user manual, usability of child protection and usability of chair installation. AEMV synthetic weight assignment modeling is used to decide individual weight.

4.1. AHP-based Weighting.

Matrix should be constructed based on vectorization, which means all raw data shall be converted into values in standardized format for direct comparison, according to defined measurement scale system[19] Saaty adopted reciprocal 1-9 scale of measurement for AHP vectorization[20] Elements of present hierarchy in AHP modeling are compared to an element of higher hierarchy. Pairwise comparison is commonly used [21]. As for comparison to an element of higher hierarchy, a criterion \( z_{ij} \) indicates the comparative importance between element \( i \) and element \( j \) in the present hierarchy. \( z_{ij} \) is usually a positive integer from 1-9 and the reciprocal thereof \( z_{ij}^{-1} \) composes so-called comparison matrix:

\[
Z = (z_{ij})_{n \times n} = \begin{bmatrix}
z_{11} & z_{12} & \cdots & z_{1n} \\
z_{21} & z_{22} & \cdots & z_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
z_{n1} & z_{n2} & \cdots & z_{nn}
\end{bmatrix}
\] (2)

If \( i = j \), \( z_{ij} = 1 \); other values are defined with reciprocal 1-9 scale. Refer to Table 1.
Table 1. Reciprocal 1-9 scale of measurement

| $z_{ij}$ | Value selection |
|----------|-----------------|
| 1        | element $i$ and element $j$ equally important |
| 3        | in comparison between element $i$ and element $j$, $i$ is slightly more important than $j$ |
| 5        | in comparison between element $i$ and element $j$, $i$ is obviously more important than $j$ |
| 7        | in comparison between element $i$ and element $j$, $i$ is strongly more important than $j$ |
| 9        | in comparison between element $i$ and element $j$, $i$ is extremely more important than $j$ |
| $1/3$    | element $i$ is less important in comparison with element $j$ |
| $1/5$    | element $i$ is obviously less important in comparison with element $j$ |
| $1/7$    | element $i$ is strongly less important in comparison with element $j$ |
| $1/9$    | element $i$ is extremely less important in comparison with element $j$ |

Pairwise comparison is adopted for judgement matrix $Z$. Its maximum eigenvalue $\lambda_{\text{max}}$ and associated eigenvector $P_m$ can be calculated. $P_m$ is normalized to present the weight vector of various elements at same hierarchy. Conformity of the comparison-driven judgement matrix $Z$ need be verified by calculating conformity rate $C.R.$ Verification is positive in case $C.R. < 0.1$, otherwise reconstruction is required. $C.R.$ formulation is shown below: $C.R. = C.I./R.I.$

Of the coefficients: $C.I.$ is conformity index, $C.I. = (\lambda_{\text{max}} - n) / (n - 1)$; $n$ means the order of the comparison-driven judgement matrix $Z$; $R.I.$ is random index, with its value selection shown in Table 2.

Table 2. Random index $R.I.$ value selection

| $n$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----|---|---|---|---|---|---|---|---|---|
| $R.I.$ | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

Scale is given in Table 1, judgement matrix is then acquired shown as Table 3 below, thanks to expertise. Calculated maximum eigenvalue is $\lambda_{\text{max}} = 3.0092$; $C.I. = 0.0046$ is derived according to conformity index formulation; $C.R. = 0.0088 << 0.1$ is derived according to conformity rate formulation, indicating qualified conformity verification of judgement matrix. Eigenvector values are normalized to obtain weight vector $W_s = [0.1091 \ 0.1891 \ 0.3509 \ 0.3509]$ based on AHP method.

Table 3. AHP-based judgement matrix

| $Z$ | $M_1$ | $M_2$ | $M_3$ | $M_4$ |
|-----|-------|-------|-------|-------|
| $M_1$ | 1     | 1/2   | 1/3   | 1/3   |
| $M_2$ | 2     | 1     | 1/2   | 1/2   |
| $M_3$ | 3     | 2     | 1     | 1     |
| $M_4$ | 4     | 2     | 1     | 1     |

4.2. Entropy-based Weighting.

Literature [22] displays usability evaluation results of 6 child-safety chairs. Matrix composed of evaluation scores is shown in Table 4.
Table 4. Matrix usability indexes evaluation values

|       | $M_1$ | $M_2$ | $M_3$ | $M_4$ |
|-------|-------|-------|-------|-------|
| CSR-1 | 2.283 | 2.861 | 2.321 | 1.738 |
| CSR-2 | 2.501 | 2.112 | 2.298 | 2.825 |
| CSR-3 | 1.595 | 1.882 | 2.356 | 2.437 |
| CSR-5 | 1.595 | 1.876 | 2.155 | 1.257 |
| CSR-6 | 1.867 | 2.282 | 2.623 | 1.896 |

When applying Entropy method, index $j$ has its entropy value $e_j$ calculated:

$$e_j = -k \sum_{i=1}^{n} P(x_{ij}) \ln P(x_{ij}), \quad e_j > 0, \quad k > 0.$$  

Wherein $x_{ij}$ is evaluation score of CSR $i$’s index $j$;

$$P(x_{ij}) = \frac{1}{n} \frac{\sum_{i=1}^{n} x_{ij}}{x_{ij} (n! / r!(n-r)!)}.$$  

With regard to the present evaluation, $n = 6$, while $k = 1 / \ln 6 = 0.5581$. Calculation is:

$$E = \{e_1, e_2, e_3, e_4\} = \{0.9917, 0.9937, 0.9965, 0.9791\}$$  

(3)

Index $j$ has coefficient variation $g_j$ calculated: $G_j = 1 - e_j$, then the calculation is:

$$G = \{g_1, g_2, g_3, g_4\} = \{0.0083, 0.0063, 0.0035, 0.0209\}$$  

(4)

Provided the normalization formulation $w_j = g_j / \sum_{j=1}^{n} g_j$, weight vector values shall be decided by Entropy calculation:

$$W_{O1} = \{w_1, w_2, w_3, w_4\} = \{0.2131, 0.1609, 0.0892, 0.5367\}$$  

(5)

4.3. Mean-Variance-based Weighting.

Refer to the usability evaluation values given in Figure 4. Calculation of mathematically expected value is performed as $\overline{x_j} = \frac{1}{n} \sum_{i=1}^{n} x_{ij}$, and get values

$$\overline{X} = \{\overline{x_1}, \overline{x_2}, \overline{x_3}, \overline{x_4}\} = \{2.0065, 2.1790, 2.4588, 2.1630\};$$  

Calculation of mean variance is performed as: $v_j = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_{ij} - \overline{x_j})^2}$, and get values:

$$V = \{v_1, v_2, v_3, v_4\} = \{0.3784, 0.3672, 0.3058, 0.6363\}$$

Provided the normalization formulation $w_j = v_j / \sum_{j=1}^{n} v_j$, weight vector values shall be decided by Mean Variance calculation:

$$W_{O2} = \{w_1, w_2, w_3, w_4\} = \{0.2242, 0.2176, 0.1812, 0.3770\}$$  

(6)

4.4. Synthesis of Weight Values and Result Analysis.

Entropy-based $W_{O1}$ and Mean-Variance-based $W_{O2}$ are synthesized to get individual weight vector $W_{O}$:

$$W_{O} = \{w_{O1}, w_{O2}, w_{O2}, w_{O2}\} = \{0.2186, 0.1871, 0.1271, 0.4498\}$$  

(7)
\( W' \) is later normalized to get \( W_o = \{0.2225\ 0.1904\ 0.1294\ 0.4578\} \). Vector set \( W_s \) is organized from the minimum to the maximum: \( \{0.1091\ 0.1891\ 0.3509\ 0.3509\} \), and calculate coefficient variation of individual weight \( W_s \):

\[
T_s = \frac{2}{4} (1 \times 0.1091 + 2 \times 0.1891 + 3 \times 0.3509 + 4 \times 0.3509) - \frac{4+1}{4} = 0.2218
\]  

Calculation of coefficients as \( \alpha = \frac{n}{n-1} \frac{T_s}{4-1} \times 0.2218 = 0.3; \ \beta = 1 - \alpha = 1 - 0.2957 = 0.7 \); \( W_s \) and \( W_o \) are now synthesized via additive ensemble into weight vector set \( W \):

\[
W = 0.3 \{0.1091\ 0.1891\ 0.3509\ 0.3509\} + 0.7 \{0.2225\ 0.1904\ 0.1294\ 0.4578\}
\]

\[
= \{0.1885\ 0.1900\ 0.1959\ 0.4257\}
\]  

According to weight values shown in Figure 2, chair installation usability \( M_4 \) has the greatest weight, regardless of adopted weighting methods. Weighting both expertise and test data, AEMV synthetic approach produces a more logical distribution of weights, thanks to experience and preference of experts in decision making as well as correlation and features of objective data series.

\[
\begin{array}{c|c|c|c|c}
\hline
\text{weight value} & \text{AHP method} & \text{Entropy method} & \text{Mean Variance method} & \text{AEMv synthetic method} \\
\hline
\text{w1} & 0.1091 & 0.2131 & 0.2242 & 0.1885 \\
\text{w2} & 0.1891 & 0.1609 & 0.2176 & 0.19 \\
\text{w3} & 0.3509 & 0.0892 & 0.1812 & 0.1959 \\
\text{w4} & 0.3509 & 0.5367 & 0.377 & 0.4257 \\
\hline
\end{array}
\]  

\textbf{Figure 2. Weight values based on various weighting methods}

\textbf{5. Conclusions}

Child-safety chairs are perceptibly less applied in China in comparison to the situation in developed countries. Child-safety chair evaluation serves rational and correct purchase and use of every consumer. Usability is a decisive factor of any child safety chair in assessing its functions, making purchase decision, and using it properly and effectively. AHP method brings about less proper results due to intrinsic limitation when deciding index weights of usability evaluation of any child-safety chair products. AEMV synthetic weight assignment modeling as a combined method is whereas derived on the basis of AHP method, Entropy method and Mean Variance method. Expertise and objective test data are also reckoned in. Comparative study on results demonstrates the weight assignment mechanism of the present synthetic weighting as a more scientifically objective approach, with more logical outcomes of usability evaluation.
Acknowledgments

This work was financially supported by National Fund for Fundamental Research (282017Y-5303, 282018Y-5973).

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